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**University of Potsdam**  
Faculty of Human Sciences  
DIVISION OF TRAINING AND MOVEMENT SCIENCE

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**FACTORS INFLUENCING THE EFFECTIVENESS OF  
BALANCE AND RESISTANCE TRAINING  
IN OLDER ADULTS**

An academic thesis submitted to  
the Faculty of Human Sciences of the University of Potsdam

for the degree  
**Doctor of Philosophy (Dr. phil.)**

by  
**André Lacroix**

born in Karlsruhe, Germany

Heidelberg, 2017

Dean of the faculty: Prof. Barbara Höhle, PhD

First reviewer: Prof. Urs Granacher, PhD (Division of Training and Movement Science, University of Potsdam)

Second reviewer: Prof. Markus Gruber, PhD (Chair of Training and Movement Science, University of Konstanz)

Chairperson of the Examining Board: Prof. Michael Rapp, MD, PhD (Division of Social and Preventive Medicine, University of Potsdam)

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Place, Date

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André Lacroix



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**Abstract (English)**

*Background and objectives:* Age-related losses of lower extremity muscle strength/power and deficits in static and particularly dynamic balance are associated with impaired functional performance and the occurrence of falls. It has been shown that balance and resistance training have the potential to improve balance and muscle strength in healthy older adults. However, it is still open to debate how the effectiveness of balance and resistance training in older adults is influenced by different factors. This includes the role of trunk muscle strength, the comprehensive effects of combined balance and resistance training, and the role of exercise supervision. Therefore, the primary objectives of this doctoral thesis are to investigate the relationship between trunk muscle strength and balance performance and to examine the effects of an expert-based balance and resistance training protocol on various measures of balance and lower extremity muscle strength/power in older adults. Furthermore, the impact of supervised versus unsupervised balance and/or resistance training interventions in the elderly will be evaluated.

*Methods:* Healthy older adults aged 63-80 years were included in a cross-sectional study, a longitudinal study, and a meta-analysis (range group means meta-analysis: 65.3-81.1 years) registering balance and muscle strength/power performance. Different measures of balance (i.e., static/dynamic, proactive, reactive) were examined using clinical (e.g., Romberg test) and instrumented tests (e.g., 10 meter walking test on a sensor-equipped walkway). Isometric strength of the trunk muscles was assessed using instrumented trunk muscle strength apparatus and lower extremity dynamic muscle strength/power was examined using clinical tests (e.g., Chair Stand Test). Further, a combined balance and resistance training protocol was applied to examine training-induced effects on balance and muscle strength/power as well as the role of supervision in older adults.

*Results:* Findings revealed that measures of trunk muscle strength and static steady-state balance as well as specific measures of dynamic steady-state balance were significantly associated in the elderly ( $0.42 \leq r \leq 0.57$ ). Combined balance and resistance training significantly improved older adults' static/dynamic steady-state (e.g., Romberg test; habitual gait speed), proactive (e.g., Timed Up and Go Test), and reactive balance (e.g., Push and Release Test) as well as muscle strength/power (e.g., Chair Stand Test) ( $0.62 \leq \text{Cohen's } d \leq 2.86$ ; all  $p < 0.05$ ). Supervised compared to unsupervised balance and/or resistance training was superior in enhancing older adults' balance and muscle strength/power performance regarding all observed outcome categories [longitudinal study: effects for the supervised group  $0.26 \leq d \leq 2.86$ , ef-



fects for the unsupervised group  $0.06 \leq d \leq 2.30$ ; meta-analysis: all between-subject standardized mean differences ( $SMD_{bs}$ ) in favor of the supervised training programs  $0.24-0.53$ ]. The meta-analysis additionally showed larger effects in favor of supervised interventions when compared to completely unsupervised interventions ( $0.28 \leq SMD_{bs} \leq 1.24$ ). These effects in favor of the supervised programs faded when compared with studies that implemented a small amount of supervised sessions in their unsupervised interventions ( $-0.06 \leq SMD_{bs} \leq 0.41$ ).

*Conclusions:* Trunk muscle strength is associated with steady-state balance performance and may therefore be integrated in fall-preventive exercise interventions for older adults. The examined positive effects on a large number of important intrinsic fall risk factors (e.g., balance deficits, muscle weakness) imply that particularly the combination of balance and resistance training appears to be a feasible and effective exercise intervention for fall prevention. Owing to the beneficial effects of supervised compared to unsupervised interventions, supervised sessions should be integrated in fall-preventive balance and/or resistance training programs for older adults.

**Keywords:** elderly; balance; lower extremity muscle strength/power; trunk muscle strength; balance training; resistance training; exercise supervision

**Abstract (German)**

Hintergrund und Ziele: Altersbedingte Kraft- und Gleichgewichtsverluste sind mit Funktionseinschränkungen und einem erhöhten Sturzrisiko assoziiert. Kraft- und Gleichgewichtstraining haben das Potenzial, das Gleichgewicht und die Maximalkraft/Schnellkraft von gesunden älteren Menschen zu verbessern. Es ist jedoch noch nicht hinreichend untersucht, wie die Effektivität solcher Übungsprogramme von verschiedenen Faktoren beeinflusst wird. Hierzu gehören die Rolle der Rumpfmuskulatur, die Effekte von kombiniertem Kraft- und Gleichgewichtstraining sowie die Effekte der Trainingsanleitung. Die primären Ziele dieser Dissertation bestehen daher in der Überprüfung der Zusammenhänge von Rumpfkraft und Gleichgewichtsvariablen und der Effekte von kombiniertem Kraft- und Gleichgewichtstraining auf ein breites Spektrum an intrinsischen Sturzrisikofaktoren bei älteren Menschen. Ein wesentliches Ziel dieser Dissertation ist zudem die Überprüfung der Auswirkungen von angeleitetem gegenüber unangeleitetem Kraft- und/oder Gleichgewichtstraining auf Variablen des Gleichgewichts und der Maximal-/Schnellkraft bei älteren Menschen.

Methoden: Gesunde ältere Erwachsene im Alter zwischen 63 und 80 Jahren wurden in einer Querschnittsstudie, einer Längsschnittstudie und einer Metaanalyse untersucht (Gruppenmittelwerte Meta-Analyse: 65.3-81.1 Jahre). Messungen des Gleichgewichts (statisches/dynamisches, proaktives, reaktives Gleichgewicht) wurden mittels klinischer (z. B. Romberg Test) und instrumentierter Tests (z. B. 10 Meter Gangtest inklusive elektrischer Erfassung von Gangparametern) durchgeführt. Die isometrische Maximalkraft der Rumpfmuskulatur wurde mit speziellen Rumpfkraft-Maschinen gemessen. Für die Überprüfung der dynamischen Maximal-/Schnellkraft der unteren Extremität wurden klinische Tests (z. B. Chair Stand Test) verwendet. Weiterhin wurde ein kombiniertes Kraft- und Gleichgewichtstraining durchgeführt, um trainingsbedingte Effekte auf Gleichgewicht und Maximal-/Schnellkraft sowie die Effekte der Trainingsanleitung bei älteren Erwachsenen zu untersuchen.

Ergebnisse: Die Ergebnisse zeigten signifikante Korrelationen zwischen Rumpfkraft und statischem sowie ausgewählten Parametern des dynamischen Gleichgewichts ( $0.42 \leq r \leq 0.57$ ). Kombiniertes Kraft- und Gleichgewichtstraining verbesserte das statische/dynamische (z. B. Romberg Test, Ganggeschwindigkeit), proaktive (z. B. Timed Up and Go Test) und reaktive Gleichgewicht (z. B. Push and Release Test) sowie die Maximal-/Schnellkraft (z. B. Chair Stand Test) von gesunden älteren Menschen ( $0.62 \leq \text{Cohen's } d \leq 2.86$ ; alle  $p < 0.05$ ). Angeleitetes Training führte verglichen mit unangeleitetem Training zu größeren Effekten bei Gleichgewicht und Maximal-/Schnellkraft [Längsschnittstudie: Effekte in der angeleiteten

Gruppe  $0.26 \leq d \leq 2.86$ , Effekte in der unangeleiteten Gruppe  $0.06 \leq d \leq 2.30$ ; Metaanalyse: alle Standardisierte Mittelwertdifferenzen ( $SMD_{bs}$ ) zugunsten der angeleiteten Programme  $0.24-0.53$ ]. Die Metaanalyse zeigte zudem größere Effekte zugunsten der angeleiteten Programme, wenn diese mit komplett unbeaufsichtigten Programmen verglichen wurden ( $0.28 \leq SMD_{bs} \leq 1.24$ ). Diese Effekte zugunsten der angeleiteten Interventionen wurden jedoch abgeschwächt, wenn sie mit unangeleiteten Interventionen verglichen wurden, die wenige zusätzliche angeleitete Einheiten integrierten ( $-0.06 \leq SMD_{bs} \leq 0.41$ ).

Schlussfolgerungen: Eine Aufnahme von Rumpfkraftübungen in sturzpräventive Trainingsprogramme für ältere Menschen könnte die Verbesserung von Gleichgewichtsparametern positiv beeinflussen. Die positiven Effekte auf eine Vielzahl wichtiger intrinsischer Sturzrisikofaktoren (z. B. Gleichgewichts-, Kraftdefizite) implizieren, dass besonders die Kombination aus Kraft- und Gleichgewichtstraining eine durchführbare und effektive sturzpräventive Intervention ist. Aufgrund größerer Effekte von angeleitetem im Vergleich zu unangeleitetem Training sollten angeleitete Einheiten in sturzpräventive Übungsprogramme für ältere Erwachsene integriert werden.

**Schlüsselwörter:** Senioren; Gleichgewicht; Maximalkraft/Schnellkraft; Rumpfkraft; Gleichgewichtstraining; Krafttraining; Übungsanleitung

**Abbreviations**

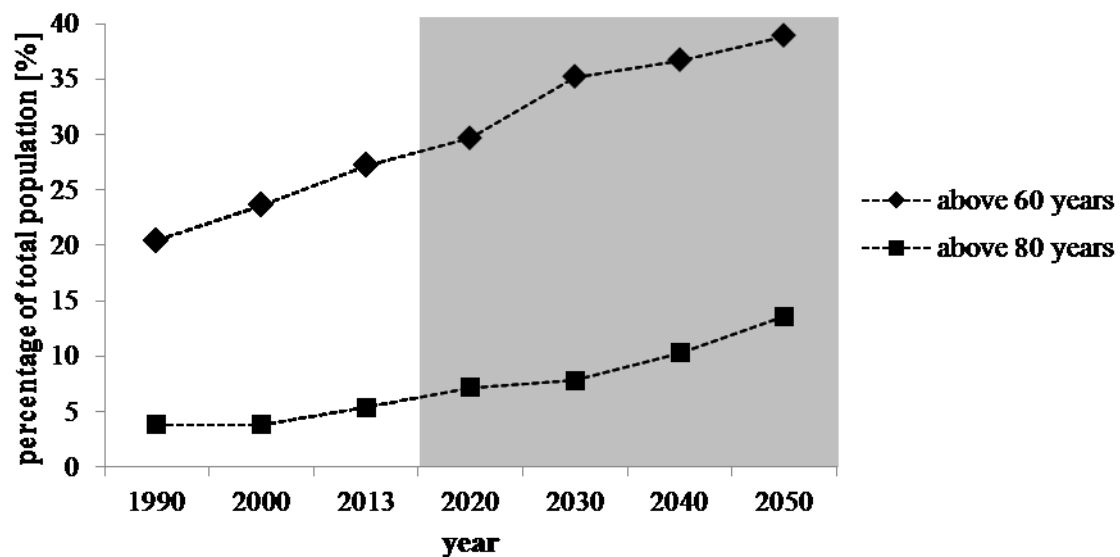
AP	anterior-posterior
BT	balance training
CoF	center of force
CoM	center of mass
CON	control group
CoP	center of pressure
CRT	combined balance and resistance training
CST	chair stand test
FRT	functional reach test
IG	intervention group
ML	mediolateral
MMSE	mini mental state examination
PRT	push and release test
RCT	randomized controlled trial
RT	resistance training
SADT	stair ascent and descent test
SAT	stair ascent test
SDT	stair descent test
SMD	standardized mean difference
SUP	supervised training program(s)
TUG	timed up and go test
UNSUP	unsupervised training program(s)

## 1. Introduction

The first chapter of this doctoral thesis briefly introduces the research problem and highlights the objectives including an overview of the four publications of the thesis.

### 1.1 Identification of the research problem

Today's societies are affected by demographic change leading to population aging. As fertility decreases and life expectancy increases, the proportion of people aged 60 years or over is rising globally. This trend of rapid aging will become particularly apparent in Europe, where 24 % are already 60 years or older and that proportion is projected to reach 34 % in 2050 (United Nations, 2015). In Germany, for example, the percentage of persons aged 60 years and above increased from 20 % to 27 % between 1990 and 2013. Population projections indicate that in 2050, 39 % of Germany's population will be 60 years or older and 14 % even 80 years or above, indicating a reinforced progression of population aging (Poetzsch & Roeßger, 2015) (Figure 1).



**Figure 1:** Percentage of people aged 60 years or over and 80 years or over within Germany's total population according to Poetzsch & Roeßger (2015). The grey background marks projected data.

Older adults aged 80+ years are expected to be the fastest growing group in Germany's population. Consequently, demographic change strongly influences the oldest segments of our societies.

Besides major demographic changes, the oldest age groups are affected by a decline in motor performance. With increasing age, the level of motor performance is impaired due to biological aging and physical inactivity (Granacher, Zahner, & Gollhofer, 2008). Responsible degenerative processes affect the central nervous and muscular systems, resulting in impaired static/dynamic balance and muscle strength/power performance (Aagaard, Suetta, Caserotti, Magnusson, & Kjaer, 2010; Abrahamova & Hlavacka, 2008; Bohannon & Williams Andrews, 2011; Manini & Clark, 2012). Diminished performance in various tests of balance (e.g., Timed Up and Go Test, gait speed) and muscle strength/power (e.g., 5 Times Chair Rise Test) is associated with an increased risk of falls. In fact, critical thresholds in terms of fall risk were previously reported in a systematic review (Granacher, Muehlbauer, Gschwind, Pfenniger, & Kressig, 2014).

The consequences of falls pose a major personal burden and are associated with substantial economic costs (Heinrich, Rapp, Rissmann, Becker, & Konig, 2010; Sherrington et al., 2016; Stevens, Corso, Finkelstein, & Miller, 2006). Epidemiological data from Germany indicate that 29.7 % of community-dwelling men and 38.7 % of women aged 65-90 years fall at least once per year (Rapp et al., 2014). The rate of falls rises from old to oldest (Rubenstein & Josephson, 2002). About 5 to 10 % of falls cause serious injuries requiring medical treatment (Nevitt, Cummings, & Hudes, 1991; Rubenstein & Josephson, 2002; Tinetti, Doucette, Claus, & Marottoli, 1995). Such fall-related injuries increase mobility disability, nursing home admission, and mortality (Gill, Allore, Holford, & Guo, 2004; Rubenstein, 2006; Sherrington et al., 2016; Tinetti, 2003). Falls are caused by intrinsic (e.g., muscle weakness, gait disorder, cognitive impairment) and extrinsic (e.g., medication, lighting conditions, stairs) factors, or a combination of both (Rubenstein, 2006; Schott & Kurz, 2008). Regarding intrinsic fall risk factors in older adults, deficits in balance, gait instability, and muscle weakness are most important (Rubenstein, 2006). As population aging progresses globally, effective exercise programs should have the potential to mitigate age-related declines in static/dynamic balance and muscle strength/power.

Previous systematic reviews and meta-analyses have shown that appropriately designed exercise programs [i.e., balance training (BT), resistance training (RT), and combined balance and resistance training (CRT)] improve healthy older adults' static/dynamic balance (Gillespie et al., 2012; Hortobágyi et al., 2015; Howe, Rochester, Neil, Skelton, & Ballinger, 2011) and lower extremity muscle strength/power (Christie, 2011; Granacher, Muehlbauer, Zahner, Gollhofer, & Kressig, 2011), with specific single exercise interventions appearing effective in

preventing falls in older people living in the community (Campbell & Robertson, 2007; Sherrington et al., 2016).

Previous exercise programs differed in terms of various influencing factors, for example exercise/training modalities such as volume, period, frequency, amount of supervision, setting, and type of exercises. Regarding the exercises implemented in such fall-preventive exercise interventions, balance and/or lower extremity resistance exercises have traditionally been used (Granacher, Muehlbauer, Zahner et al., 2011; Liu & Latham, 2009). More recently, particularly the lay literature has promoted the importance of trunk muscle strength (TMS) for the successful performance of everyday and sports-related activities. Although previous cross-sectional studies suggest that measures of TMS/spinal mobility may modulate balance, functional performance, and falls in older adults (Kasukawa et al., 2010; Suri, Kiely, Leveille, Frontera, & Bean, 2009), they provide only preliminary evidence, as they are heterogeneous in terms of subjects and testing methodology (Granacher, Gollhofer, Hortobagyi, Kressig, & Muehlbauer, 2013). Thus, additional well-designed cross-sectional studies are needed that investigate the relationship between measures of TMS, spinal mobility, balance, and functional performance. Evidence for these relationships may substantially contribute to the development of the required tailored exercise programs that have the potential to decrease fall risk in older adults.

Recent randomized controlled trials (RCTs) and meta-analyses also indicate that particularly exercise programs involving both balance and resistance exercises may have the potential to mitigate intrinsic fall risk factors (i.e., balance/muscle strength deficits) in older adults (Freiberger et al., 2013; Sherrington et al., 2016; Suzuki, Kim, Yoshida, & Ishizaki, 2004; Zhuang, Huang, Wu, & Zhang, 2014). More specifically, Gillespie et al. (2012) showed in a meta-analysis that such CRT programs have the potential to reduce the fall rate in older adults. Despite the increasing knowledge of the effects of CRT on specific measures of balance and muscle strength/power, there is a need for further research projects investigating the comprehensive impact of easy-to-administer CRT programs on a broader range of performance measures like static/dynamic steady-state, proactive, and reactive balance as well as muscle strength/power performance. Thus, these comprehensive approaches could complement the existing knowledge about the impact of CRT in older adults and be a helpful tool for practitioners. Further, such evaluated exercise programs have not been sufficiently implemented into clinical practice due to, among other reasons, inadequate communication between researchers, policy makers and clinicians, and health system barriers including inadequate

financial resources (Gschwind, Wolf, Bridenbaugh, & Kressig, 2011; Lord, Sherrington, Cameron, & Close, 2011; Shier, Trieu, & Ganz, 2016). Consequently, in order to facilitate widespread implementation, easy-to-administer fall prevention programs that address new research evidence should be developed by multidisciplinary experts (e.g., geriatricians, sports/accident prevention scientists). One way to facilitate dissemination of such programs is the publication of study protocols (Godlee, 2001), which additionally improve the transparency of the scientific process.

Besides the lack of knowledge about the role of TMS and the comprehensive effects of CRT, there is much inconsistency in the literature with respect to the programs being delivered with or without supervision in the form of supervised facility-based programs, unsupervised home-based programs, or a combination of both (Christie, 2011; Freiberger et al., 2013; Gillespie et al., 2012; Howe et al., 2011). It is important to address these inconsistencies, considering the recent hypothesis that group- and home-based training programs are equally effective in preventing falls (Gillespie et al., 2012; Sherrington et al., 2016). Training programs delivered at home without supervision may reduce costs and increase the number of people participating in fall prevention programs (Cohen-Mansfield, Marx, & Guralnik, 2003; Franco et al., 2015). While these are important issues, the physiological effectiveness of an exercise program relative to balance, mobility, and muscle strength/power is at least of the same significance.

Preceding studies investigating the effects of supervised versus unsupervised CRT provided preliminary evidence, since they were heterogeneous in terms of results (Almeida et al., 2013; Cyarto, Brown, Marshall, & Trost, 2008b; Donat & Oezcan, 2007; Helbostad, Sletvold, & Moe-Nilssen, 2004a; van Roie et al., 2010; Wu, Keyes, Callas, Ren, & Bookchin, 2010) and used limited methodological approaches (Helbostad et al., 2004a; Tuunainen et al., 2013). Consequently, there is a need for RCTs that provide a clearer and more comprehensive view of the effects of exercise supervision in older adults. Additionally, a systematic comparison of the two delivery methods (i.e., supervised, unsupervised) regarding BT and/or RT interventions in healthy older adults is lacking. A systematic review and meta-analysis could provide the most reliable evidence (Burns, Rohrich, & Chung, 2011; Ellis, 2011). Thereby, the findings of previous heterogeneous studies (Cyarto, Brown, Marshall, & Trost, 2008a; Donat & Oezcan, 2007; Wu et al., 2010) will be reviewed on a higher evidence level.



## 1.2 Objectives of the doctoral thesis

The aims of this doctoral thesis are based on the aforementioned gaps in the literature regarding factors potentially influencing the effectiveness of balance and resistance training in older adults. Considering the lack of knowledge about the role of TMS and the effects of CRT as well as the unresolved role of supervision in such programs, there is a need for studies addressing these inconsistencies in order to provide simple and effective exercise interventions that counteract intrinsic fall risk factors in older adults.

Thus, the objectives of this doctoral thesis were to (a) investigate the relationship between measures of TMS, spinal mobility, balance, and functional performance (Publication I), (b) publish a study protocol for a RCT that contains a freely available, expert-based, and easily reproducible CRT training protocol (Publication II), (c) examine the effects of this CRT protocol compared to an inactive control group (CG) on measures of balance and lower extremity muscle strength/power (Publication III), (d) compare the effects of a supervised versus unsupervised CRT on the aforementioned measures (Publication III), and (e) evaluate the effects of supervised compared to unsupervised exercise interventions (BT, RT, and CRT) in healthy older adults using a meta-analytic approach (Publication IV). For this purpose, four publications were drafted that build on each other: a cross-sectional study (Publication I), a study protocol for a longitudinal study (Publication II), a longitudinal study (Publication III), and a systematic review and meta-analysis (Publication IV). The publications will be cited in the present thesis with the following numbering:

- I Granacher, U., Lacroix, A., Roettger, K., Gollhofer, A., & Muehlbauer, T. (2014). **Relationships between trunk muscle strength, spinal mobility, and balance performance in older adults.** *Journal of aging and physical activity*, 22(4), 490-498. doi: 10.1123/japa.2013-0108  
The final publication is available at <http://journals.humankinetics.com/doi/abs/10.1123/japa.2013-0108>
- II Gschwind, Y. J., Kressig, R. W., Lacroix, A., Muehlbauer, T., Pfenninger, B., & Granacher, U. (2013). **A best practice fall prevention exercise program to improve balance, strength/power, and psychosocial health in older adults: study protocol for a randomized controlled trial.** *BMC Geriatrics*, 13, 105. doi: 10.1186/1471-2318-13-105

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The final publication is available at <https://bmcgeriatr.biomedcentral.com/articles/10.1186/1471-2318-13-105>

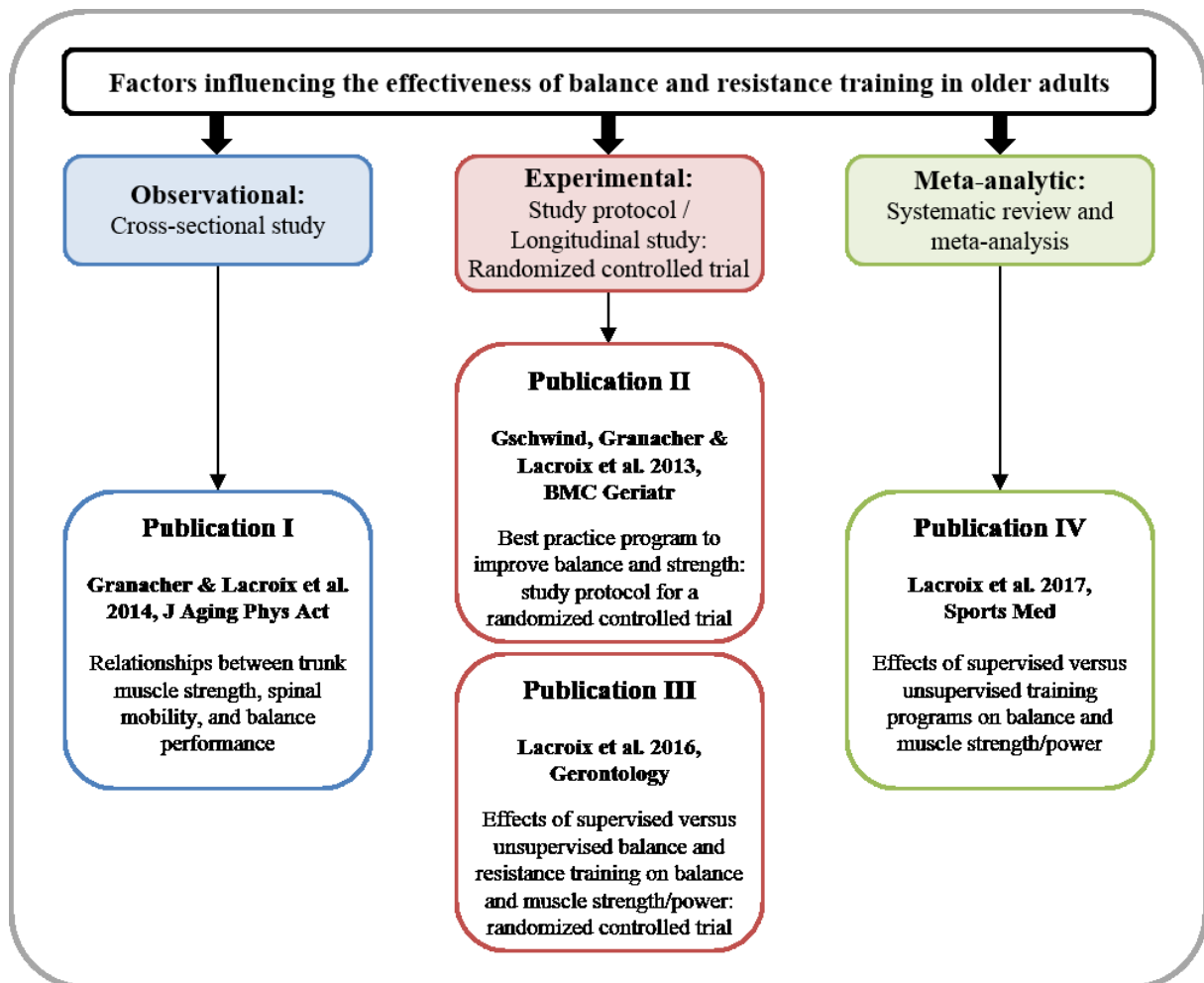
- III Lacroix, A., Kressig, R. W., Muehlbauer, T., Gschwind, Y. J., Pfenninger, B., Bruegger, O., & Granacher, U. (2016). **Effects of a supervised versus an unsupervised combined balance and strength training program on balance and muscle power in healthy older adults: a randomized controlled trial.** *Gerontology*, *62*(3), 275-288. doi: 10.1159/000442087

The final publication is available at <https://www.karger.com/Article/FullText/442087>

- IV Lacroix, A., Hortobágyi, T., Beurskens, R., & Granacher, U. (2017). **Effects of supervised vs. unsupervised training programs on balance and muscle strength in older adults: a systematic review and meta-analysis.** *Sports Medicine*, *47*(11), 2341-2361. doi: 10.1007/s40279-017-0747-6

The final publication is available at <https://link.springer.com/article/10.1007/s40279-017-0747-6>

The results of these studies may contribute to the clarification of modalities that potentially influence the effectiveness of balance and resistance training in older adults and complement existing recommendations. Clinicians, practitioners, and therapists could directly apply the new insights to ensure optimal training effects on important intrinsic fall risk factors. Figure 2 gives a schematic overview of the four publications of the present doctoral thesis that aimed at investigating the deduced research problems on observational, experimental, and meta-analytic levels.



**Figure 2:** Schematic overview of the publications (I to IV) included in this doctoral thesis. Factors potentially influencing the effectiveness of balance and resistance training in older adults are examined in a structured approach with observational, experimental, and meta-analytic publications that build on each other.

The study protocol of Publication II was based on the literature and the findings of Publication I and contained a best practice fall prevention program. In Publication III, the aforementioned program was evaluated regarding its effectiveness in a supervised compared to an unsupervised implementation. The results of this RCT were included in the systematic review and meta-analysis of Publication IV, increasing its generalizability.

## **2. Theoretical analysis**

In the everyday lives of older people, a sufficient level of motor performance is necessary to securely perform various tasks such as standing, walking, rising from a chair, climbing stairs, or more complex activities like shopping. The present chapter will outline deficits in balance and muscle strength/power performance and discuss physiological reasons for the impaired motor performance in old age. Furthermore, an overview of risk factors for falls as well as BT and RT interventions in older adults will be given. Finally, the chapter will discuss modalities of supervision of such exercise interventions.

### **2.1 Impaired motor performance in older adults**

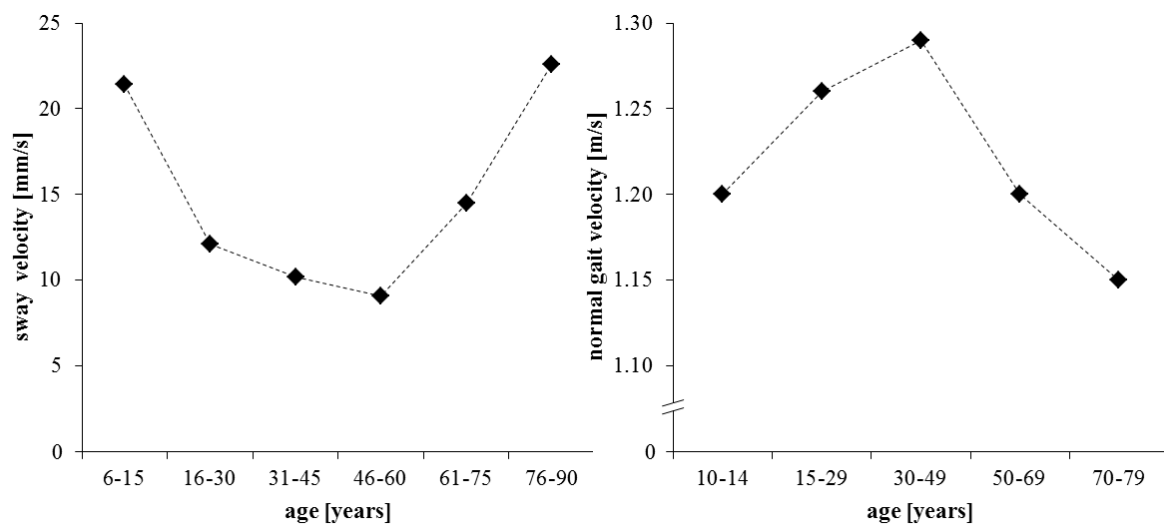
The process of aging along with physical inactivity results in a diminished neuromuscular performance in terms of deficits in balance as well as muscle strength/power (Granacher et al., 2008). Multiple quantitative and qualitative processes in the central nervous and muscular systems seem to be associated with this decline, altogether resulting in an increased risk of falling.

#### *2.1.1 Balance deficits*

Balance involves controlling the body's position in space for the dual purposes of stability and orientation (Shumway-Cook & Woollacott, 2017). Postural orientation is defined as the ability to maintain an appropriate relationship between the body and the environment for a task (Horak, 2006). Postural stability is the ability to control the center of mass (CoM) in relationship to the base of support (Shumway-Cook & Woollacott, 2017). Different authors used the term 'balance' interchangeably with the term 'postural control', others used both terms separately. In this thesis, the terms 'balance' and 'postural control' are used synonymously, as proposed by Shumway-Cook and Woollacott (2017).

Maintaining balance during standing and sitting (static conditions) is different from maintaining balance when moving (dynamic condition). During static conditions, the base of support (e.g., feet) remains stationary and only the CoM moves. In contrast, during dynamic conditions both the base of support and the CoM shift (Woollacott & Tang, 1997). If the task is to keep the CoM within the base of support or the limit of stability (the maximal estimated sway angle of the CoM), different aspects of balance control are necessary. Shumway-Cook and Woollacott (2017) proposed to differentiate between static/dynamic steady-state (i.e., maintaining a stable position in sitting, standing, and walking), proactive (i.e., anticipation and

accomplishment of a predicted disturbance), and reactive (i.e., compensation for an unexpected disturbance) balance control. In fact, Muehlbauer et al. (2012) found no significant correlations between measures of steady-state, proactive and reactive balance ( $r = 0.01-0.30$ ), suggesting that balance control is highly task-specific. There is also evidence that the ability to control posture is a dynamic process across the life span (Granacher, Muehlbauer, & Gruber, 2012). Previous studies have reported a U-shaped dependency for age and static steady-state balance, as well as an inverted U-shaped dependency for age and dynamic steady-state balance (see Figure 3).



**Figure 3:** Development of static (i.e., sway velocity) and dynamic (i.e., habitual gait velocity) steady-state balance across the life span according to Granacher et al. (2011). Data extracted from Hytoenen et al. (1993) and Oberg et al. (1993).

For example, Springer et al. (2007) showed in a prospective study that static steady-state balance is age-specific. They assessed performance in single leg stance with eyes opened and eyes closed (time in s) for a randomly selected sample and compared different age groups (i.e., ages 18-99). Performance decreased for older compared to younger age groups and differences became more pronounced after the age of 60. This is in line with other studies comparing reliable normative data for other domains of static steady-state balance (e.g., sway of the CoP on a force platform) among age groups (Era et al., 2006). When performing static balance tasks with increasing task difficulty, older adults show greater CoP excursions, EMG activity and joint displacement than their younger counterparts (Amiridis, Hatzitaki, & Arabatzi, 2003). Additionally, older adults seem to rely more on a hip strategy for balance

recovery, if balance is challenged by increased task difficulty during standing (Amiridis et al., 2003).

Regarding dynamic steady-state balance, slower gait speeds (Granacher, Muehlbauer, Bridenbaugh, Wehrle, & Kressig, 2010; Oberg et al., 1993), shorter stride length, a wider base of support, a greater proportion of the gait cycle in double leg support (Aboutorabi, Arazpour, Bahramizadeh, Hutchins, & Fadayevatan, 2016), and enhanced stride-to-stride variability during single- and multi-task walking (motor/cognitive interference tasks) (Callisaya, Blizzard, Schmidt, McGinley, & Srikanth, 2010; Granacher, Bridenbaugh, Muehlbauer, Wehrle, & Kressig, 2011) have been detected in older compared to younger adults. In terms of proactive balance, age-related performance declines have been reported for several tests, including the Timed Up and Go Test (TUG) and the Functional Reach Test (FRT) (Bohannon, 2006; Isles, Choy, Steer, & Nitz, 2004). Older adults also show deficits in the compensation of unexpected perturbation impulses during standing and walking. This age-related decline in reactive balance performance is evidenced in slower onset latencies, reduced reflex activities, increased antagonist coactivation, and longer burst durations of muscles (Granacher, Gruber, & Gollhofer, 2010; Lin & Woollacott, 2002; Tang & Woollacott, 1998). Additionally, age-specific deterioration in balance test battery performance (e.g., Berg Balance Scale) has been reported (Steffen, Hacker, & Mollinger, 2002).

To summarize the presented findings, older adults' static/dynamic steady-state balance (single and dual task), proactive balance, reactive balance, and balance test battery performance are significantly lower than that of younger adults. For many balance tests that represent these aspects of balance control, critical thresholds associated with an increased risk of falling were reported in the literature. For example, a standing time of  $< 30$  s in the single leg stance (Hurvitz, Richardson, Werner, Ruhl, & Dixon, 2000), a habitual gait speed of  $< 1$  m/s (van Kan et al., 2009), a duration of  $\geq 13.5$  s to complete the TUG (Shumway-Cook, Brauer, & Woollacott, 2000), a score of 0.9 in the reactive Push and Release Test (PRT) (Valkovic, Brozová, Bötzel, Růzicka, & Benetin, 2008), and a score of  $\leq 49$  on the Berg Balance Scale (Shumway-Cook, Baldwin, Polissar, & Gruber, 1997) are associated with an increased risk of falling. For a review, see Granacher et al. (2014). In fact, balance disorders are one of the most important intrinsic fall risk factors in older adults (Rubenstein, 2006).

*What are the reasons for balance deficits in older adults?* Recent studies have highlighted the fact that the control of posture cannot solely be attributed to reflex activities, but is also dependent on the processing in cortical areas (Jacobs & Horak, 2007; Taube, Gruber, &

Gollhofer, 2008). This includes the processing and integration of sensory information provided by the visual, proprioceptive, and vestibular system on spinal and cortical levels (Granacher et al., 2008). Various structural and functional changes in the aging neuromuscular system have an impact on postural control. Structural changes lead to both quantitative and qualitative degeneration of peripheral, spinal, and cortical structures, whereas functional changes imply modifications in how these structures operate during a specific postural task (Papegaaij, Taube, Baudry, Otten, & Hortobágyi, 2014). More specifically, age-related changes on the peripheral and spinal levels include, but are not limited to, a decline in the number of sensory/motor neurons and interneurons (Aagaard et al., 2010; Granacher et al., 2008; McNeil, Doherty, Stashuk, & Rice, 2005; Terao et al., 1996) and a decline in fiber density (Jacobs & Love, 1985). Additionally, there seems to be an age-related reduction in the quality and quantity of muscle spindles, which are an important structure for postural control (Granacher et al., 2008; Kararizou, Manta, Kalfakis, & Vassilopoulos, 2005; Papegaaij et al., 2014). These processes result in a decreased nerve conduction velocity and response amplitude, and might therefore negatively affect adequate responses to balance threats (Granacher et al., 2008; Papegaaij et al., 2014). On cortical levels, other age-related structural changes contribute to the dysfunction of the neuromuscular system. These structural changes are related to gray and white matter volume, which decreases during the aging process (Papegaaij et al., 2014). The decline of gray matter volume has been reported to occur in the prefrontal and parietal cortices, as well as sensory and motor areas (Papegaaij et al., 2014). Reduction particularly in gray matter volume seems to be associated with motor performance outcomes, evidenced by declines in drawing and reaching tasks (Kennedy & Raz, 2005; Sridharan et al., 2012). Decreases in white matter integrity are associated with choice reaction tasks requiring central processing speed (Kerchner et al., 2012). In addition, many studies have shown that changes in cortical structures are negatively associated with balance tasks (e.g., single leg stance, gait speed, Short Physical Performance Battery) (Kido et al., 2010; Rosano et al., 2010; Ryberg et al., 2011). Since brain function is very complex, deterioration in function directly resulting from the structural changes is hard to assess. However, there is a clear trend showing that cortical control of posture is reorganized during aging, with an increase in brain activation and decrease in cortical inhibition. In addition, spinal control of posture is reorganized by a differential control of spinal reflexes. Therefore, it has recently been postulated that aging causes a reorganization of postural control (Papegaaij et al., 2014). For a review on

the relationships between structural/functional changes in the neuromuscular system and postural control in aging, see the review by Papegaaij et al. (2014).

Altogether, the aforementioned age-related changes seem to be involved in balance deficits in old age, leading to an increased risk of falling. It has to be mentioned that specific diseases [e.g., dementia (Bullain et al., 2013), polyneuropathy (Lencioni et al., 2014)], muscle weakness (Orr, 2010), and poor vision (Aartolahti et al., 2013) may contribute to the balance deficits during normal aging. However, appropriately designed BT has the potential to improve older adults' balance performance, suggesting plasticity of the involved systems and a slowing down of the age-related decline of balance control (see Chapter 2.3).

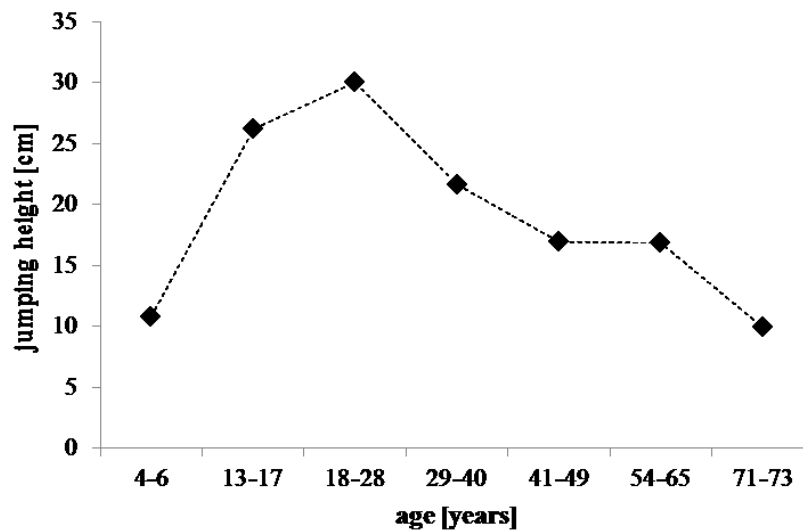
### *2.1.2 Muscle strength/power deficits*

Muscle strength and muscle power are, besides balance, also relevant components of motor performance in older adults, as many activities of daily living (Avlund, Schroll, Davidsen, Løvborg, & Rantanen, 1994; Kojima et al., 2014) as well as postural responses (Orr, 2010) require certain levels of muscle strength/power. Muscle strength can be defined as the maximum force generation capacity of an individual, whereas muscle power can be defined either as work divided by time or as the force of a muscular contraction multiplied by its velocity (Granacher et al., 2012; Macaluso & Vito, 2004). Muscle strength and muscle power can be measured during isometric, isotonic, or isokinetic contractions, using instrumented (e.g., dynamometer) or clinical tests (i.e., mostly dynamic tests with isotonic muscle contractions like chair rising or stair climbing).

Comparable to measures of balance, measures of muscle strength and muscle power develop in an inverted U-shaped curve across the life span (Figure 4) (Granacher, Muehlbauer, Gollhofer et al., 2011; Larsson, Grimby, & Karlsson, 1979). In their review, Granacher et al. (2008) reported decreases in maximal strength of 20-40 % in individuals between the ages of 30 and 80 years, depending on study design, applied methods, muscle groups tested, age groups investigated, health status, and physical activity levels. Human muscle strength/power reaches its peak between the second and third decades of life (Bosco & Komi, 1980; Granacher, Muehlbauer, Gollhofer et al., 2011; Larsson et al., 1979; Macaluso & Vito, 2004; Martin, Farrar, Wagner, & Spirduso, 2000). During the 6th decade of life, a more rapid decrease occurs, with declines of approximately 12-15 % per decade (Larsson et al., 1979; Macaluso & Vito, 2004; McNeil, Vandervoort, & Rice, 2007; Narici, Bordini, & Cerretelli, 1991; Viitasalo, Era, Leskinen, & Heikkinen, 1985). Since this trend has been validated in



studies with a cross-sectional design, cohort effects may have biased conclusions. However, there are a few studies investigating age effects on muscle strength in a longitudinal design, and most of them indicate a higher rate of decline compared to cross-sectional investigations (Frontera et al., 2000; Kallman, Plato, & Tobin, 1990; Macaluso & Vito, 2004).



**Figure 4:** Development of muscle power (i.e., jumping height during counter-movement jump) across the life span according to Granacher et al. (2011). Data extracted from Bosco and Komi (1980).

Age-related loss of strength has also been reported for different anatomical regions (Frontera, Hughes, Lutz, & Evans, 1991; Rantanen, Era, & Heikkinen, 1997; Viitasalo et al., 1985). For example, Viitasalo et al. (1985) compared maximal isometric strength (MIS) between different age groups (i.e., 31-35, 51-55, and 71-75 years). Compared with the 31-35 age group, the 71-75 age-group showed significantly decreased MIS of knee extensors (−47 %), grip strength (−42 %), trunk extensors (−42 %), trunk flexors (−35 %), and elbow flexors (−35 %). Other studies confirm the hypothesis that losses particularly in lower extremity and trunk muscle strength are substantial (Lynch et al., 1999; Sinaki, Nwaogwugwu, Phillips, & Mokri, 2001). Additionally, there is evidence that the age-related decline of muscle power is even more pronounced than the decrease in muscle strength (McNeil et al., 2007). In fact, Skelton et al. (1994) evaluated in their cross-sectional approach measures of muscle strength (MIS) and muscle power across ages ranging from 65 to 89 years. They reported an annual decrease of muscle strength of 1-2 %, whereas muscle power decreased by 3-4 % per year.

Lower levels of muscle strength and muscle power are associated with functional limitations in activities of daily living (Avlund et al., 1994; Foldvari et al., 2000; Rantanen et al., 2002; Skelton et al., 1994). Further, lower extremity and trunk muscle performance is associated with an increased risk of falling (Kasukawa et al., 2010; Macaluso & Vito, 2004; Rubenstein, 2006; Tinetti, Speechley, & Ginter, 1988; Wolfson, Judge, Whipple, & King, 1995). Critical thresholds associated with an increased risk of falls were reported for several clinical muscle strength/power tests. For example, a time of  $\geq 12$  s in the Chair Stand Test (CST) and a time of  $\geq 5$  s in the Stair Ascent and Descent Test (SADT) are associated with an increased risk of falling (Granacher, Muehlbauer et al., 2014; Tiedemann, Shimada, Sherrington, Murray, & Lord, 2008).

*What are the reasons for muscle strength/power deficits in older adults?* The decline in muscle strength and muscle power in old age is caused by different structural and functional changes affecting muscle quantity and quality. Changes in muscle quantity refer to the loss of muscle mass with advancing age (i.e., sarcopenia). Average rates of loss in elderly individuals over 70 years of age have been reported at 0.5-1.0 % per year. Although there is a great variability of individuals in any age group, most individuals over 70 years possess about 80 % of the muscle mass of those aged 20-30 years (Mitchell et al., 2012). Decreases in muscle volume have in part been attributed to age-related changes in muscle architecture. Muscle fibers become fewer in number, thinner (particularly type II fibers), and shorter (Larsson, Li, & Frontera, 1997; Narici, Maganaris, Reeves, & Capodaglio, 2003; Thom, Morse, Birch, & Narici, 2007). This contributes to the loss of force generation capacity as well as shortening velocity (Mitchell et al., 2012). In addition, the decline of muscle strength/power is influenced by neural factors. Spinal  $\alpha$ -motoneurons are gradually lost during aging, resulting in fewer motor units (Brown, 1972; Tomlinson & Irving, 1977). Although the increase in size of some motor units suggests re-innervation potential in old age, this process of re-innervation seems to be incomplete (Doherty, Vandervoort, Taylor, & Brown, 1993; Edström et al., 2007; Luff, 1998). Further, a reduced excitability of efferent pathways and an increased coactivation of antagonist muscles have been discussed as mechanisms resulting in a decreased muscle strength/power performance (Connelly, Rice, Roos, & Vandervoort, 1999; Macaluso et al., 2002).

Other factors that were discussed to be related to the loss of muscle strength/power with aging are a decrease in the number of satellite cells per muscle fiber (Kadi, Charifi, Denis, & Lexell, 2004), a tendency towards a more mixed pattern of myosin heavy chain isoforms (fibers ex-

press both type I/IIa or type IIa/IIx) (Klitgaard et al., 1990), a compromised vascularization of muscle fibers (Frontera, Meredith, O'Reilly, & Evans, 1990), increased oxidative stress (Barreiro et al., 2006), mitochondrial damage (Alway, Mohamed, & Myers, 2017), changes in tendon mechanical properties (Narici & Maganaris, 2007) and behavioral factors like nutrition (Roubenoff & Hughes, 2000) and physical activity (Evans & Cyr-Campbell, 1997). To date, the underlying mechanisms of these processes are unclear. Taken together, the mechanisms contributing to muscle strength/power deficits in old age are complex, overlapping, and interdependent (Mitchell et al., 2012). However, there is strong evidence that RT can be utilized as a countermeasure to the age-related deterioration of muscle strength/power (see Chapter 2.3).

## **2.2 Fall rate and fall risk in older adults**

Falls are frequent and serious events in older adults. Recently, Rapp et al. (2014) observed that in Germany 29.7 % of community-dwelling men and 38.7 % of women aged 65-90 years fall at least once per year. Recurrent falls occur in 10.9 % of males and 13.7 % of females per year (Rapp et al., 2014). The rate of falls rises steadily from older to oldest, with the highest rates among individuals 80 years of age and older (Campbell, Borrie, & Spears, 1989; Rubenstein & Josephson, 2002). Institutionalized persons are at highest risk for falls and subsequent complications, with a weighted average of 1.7 falls per year. Lower rates (weighted mean 0.7 falls per person annually) occur in community-living older adults (Rubenstein, 2006).

About 30 to 55 % of falls in community-dwelling elderly persons result in minor injuries (e.g., bruises, contusions) that do not receive medical attention. However, approximately 5 to 10 % of falls cause serious injuries including fractures, head injuries, and serious lacerations requiring medical treatment (Nevitt et al., 1991; Rubenstein & Josephson, 2002; Tinetti et al., 1995). Hip fractures are among the most serious fall-related injuries, and are the leading cause of hospitalization among people over 65 years (Peel, Kassulke, & McClure, 2002). Many people suffering from hip fractures do not regain mobility levels prior to their fracture. In fact, 20 to 90 % of patients who were not impaired in specific tasks (e.g., getting on and off the toilet, rising from a chair, climbing stairs) prior to their fracture are still experiencing limitations in those tasks 12 months after fracture (Magaziner et al., 2000). Other outcomes following fall-related injuries include subsequent fractures, loss of independent function, premature nursing home admission, and increased risk of mortality (Gill et al., 2004; Magaziner et al.,

2000; Magaziner, Chiles, & Orwig, 2015; Rubenstein, 2006; Sherrington et al., 2016; Tinetti, 2003).

Besides serious complications for individuals, medical treatment of fall-related injuries is a relevant economic burden to society. National fall-related costs are reported to amount to 0.9-1.5 % of the total health care expenditures with mean costs per fall-related hospitalization ranging from \$5,654 to \$42,840 USD (Heinrich et al., 2010). Fractures account for the largest portion of fall-related costs (Heinrich et al., 2010; Stevens et al., 2006).

*Why do older adults fall?* Falls are considered to be multifactorial in origin, caused by intrinsic and extrinsic factors, or a combination of both (Lord, Sherrington, Menz, & Close, 2007; Schott & Kurz, 2008). The term ‘intrinsic’ refers to personal risk factors like muscle weakness, visual impairment, or cognitive impairment, which occur due to age-related processes or diseases. Extrinsic fall risk factors imply environmental threats, including lighting conditions, floor surfaces, stairs, footwear, and medication, for example (Granacher, Muehlbauer, Gollhofer et al., 2011; Schott & Kurz, 2008). Further, situational factors have been described that combine intrinsic and extrinsic factors and are mostly related to activities of daily living. For example, an older person with balance deficits trips over the curb while crossing the street.

In a meta-analysis, Rubenstein (2006) examined the causes of falls among older adults and summarized data from 12 large retrospective studies. The most-cited category was “accident/environment-related”, which accounted for 1-53 % (mean 31 %) of falls. However, the author reported that many of the falls attributed to accidents really originated from the interaction of environmental threats and intrinsic factors that increased individual susceptibility to the hazards. Muscle weakness together with balance/gait disorders were the second most-cited category and accounted for 4-39 % of falls (mean 17 %). In another analysis, Rubenstein & Josephson (2002) conducted a univariate analysis of multiple risk factors from 16 studies which examined and compared individuals who had experienced a fall with those who had not in order to identify major fall risk factors. The most important fall risk factors were muscle weakness and balance, as well as gait deficits. Lower extremity muscle weakness increased the risk of falling 4-fold (mean relative risk/odds ratio 4.4). Balance (mean relative risk/odds ratio 2.9) and gait deficits (mean relative risk/odds ratio 2.9) have been associated with an approximately 3-fold increase in the risk of falling.

Given that the proportion of older adults will increase worldwide during the upcoming decades, there is a need for a widespread implementation of most effective exercise programs that

have the potential to mitigate age-related declines in static/dynamic balance and muscle strength/power.

## **2.3 Balance and resistance training in older adults**

During the past decades, numerous studies have investigated the effects of BT and RT in older adults and provided new insights regarding their potential as well as dose-response relationships. The benefits of BT and/or RT can be seen as a countermeasure to the age-related declines in motor performance, namely balance deficits and muscle weakness. This chapter will summarize the main findings of these studies and outline the recent trends in this field of research as well as the existing gaps in the literature.

### *2.3.1 Balance training in older adults*

Comparable training protocols that aimed at improving balance/postural control have been referred to in the literature as “balance training,” “sensorimotor training,” “neuromuscular training,” or “proprioceptive training” (Taube et al., 2008). Since the term ‘balance training’ excludes any physiological structures and describes the progress in performing a particular skill, it has been proposed as the most appropriate term (Lesinski, Hortobágyi, Muehlbauer, Gollhofer, & Granacher, 2015a; Taube et al., 2008). Therefore, the term ‘balance training’ (BT) will be used throughout this doctoral thesis. Primarily, BT aims at improving balance control during different tasks. BT exercises typically involve tasks with increasing difficulty that challenge the ability to maintain the body’s CoM within manageable limits of the base of support, including exercises in standing and moving positions (Howe et al., 2011).

Traditionally, BT has been used for rehabilitation purposes (ankle and knee joint injuries), but over the last 20 years, the application area has expanded into the field of prevention in older adults (Granacher, Muehlbauer, Zahner et al., 2011). Although BT programs vary substantially regarding the applied exercises, training duration, and intensity, the positive effects of BT in older adults on measures of balance, muscle strength/power, and fall rate have been convincingly demonstrated (Gillespie et al., 2012; Granacher, Gruber, Strass, & Gollhofer, 2007; Granacher, Muehlbauer, Zahner et al., 2011; Lesinski, Hortobágyi, Muehlbauer, Gollhofer, & Granacher, 2015b). For example, Granacher, Gruber, and Gollhofer (2009) examined the effects of a 13-week BT (3 times per week, single session duration of 60 minutes, inclusion of unstable surfaces) compared to an inactive CG in older adults aged 60-80 years. After training, analyses revealed significant performance enhancements in favor of the intervention

group (IG) on the Tandem Walk Test, FRT, oscillations of a movable balance platform after an unexpected perturbation, and activation of muscles during the compensation of platform and gait perturbations. Weighted effect sizes ranged from 1.00 to 2.08, indicating large effects in favor of BT. These and other studies comparing the effects of BT versus inactive controls were recently aggregated in a comprehensive meta-analysis (Lesinski et al., 2015b). Analyses showed that, compared to passive controls, BT is effective in improving measures of static/dynamic steady-state (e.g., CoP displacements during single leg stance, gait speed), proactive (e.g., TUG), and reactive balance (e.g., CoP displacements after an unexpected perturbation), as well as balance test battery performance (e.g., Berg Balance Scale) in healthy older adults. Weighted effect sizes ranged from 0.44 to 1.73, indicating small to large effects in favor of BT (Lesinski et al., 2015b). Additionally, Granacher et al. (2007) reported significant increases in the maximal isometric strength of the lower extremities and maximal rate of force development after a 13-week BT on unstable surfaces in healthy older adults aged 60-80 compared to passive controls. Other studies investigating the effects of BT on muscle strength/power support the hypothesis that BT has the potential to improve muscle strength/power in younger and older adults (Gruber & Gollhofer, 2004; Gusi et al., 2012; Wu, Zhao, Zhou, & Wei, 2002). Interestingly, a recent meta-analysis on the effects of exercise in preventing falls in older adults (Sherrington et al., 2016) showed that exercise programs that included (but were not limited to) balance exercises had effects on the rate of falls with a reduction of 15 % (incident rate ratio 0.85, 95 % CI 0.71 to 1.00,  $p = 0.06$ ). This is in line with a Cochrane review investigating the effects of various single and multifactorial exercise interventions on rate of falls and risk of falling (Gillespie et al., 2012). Regarding single BT interventions versus passive controls, a statistically significant reduction in the rate of falls (rate ratio 0.72, 95 % CI 0.55 to 0.94) but not in the risk of falling (risk ratio 0.81, 95 % CI 0.62 to 1.07) was observed. However, since these calculations included only four studies with one containing functional strengthening exercises, these results are merely preliminary.

The underlying physiological mechanisms leading to functional improvements of BT in older adults are still open to debate. During the past decades, noninvasive electrophysiological and brain imaging techniques have revealed insights into the adaptations following BT. Adaptations to BT are located in different regions of the human central nervous system. On the spinal level, BT was able to modify spinal reflex circuits, leading to reduced H-reflexes (Gruber et al., 2007; Mynark & Koceja, 2002; Taube et al., 2008) in both younger and older adults. However, adaptations to BT seem to be task-specific, modifying spinal reflexes primarily in

the trained exercises and dependent on the phase of the movement (Taube et al., 2008; Taube, Kullmann et al., 2007). Following 13 weeks of BT in older adults, Granacher, Gollhofer, and Strass (2006) demonstrated enhanced reflex responses in the prime mover, decreased onset latency, and decreased angular velocity of the ankle joint complex during gait perturbations compared to a CG. This indicates altered postural control strategies during aging, which is supported by the results of a recent review (Papegaaij et al., 2014) (see Chapter 2.1.1). Adaptations to BT are not only observed in the spinal system but also in supraspinal structures. It has been shown that improved balance performance after BT was associated with cortical plasticity. Taube et al. (2007) examined spinal and cortical adaptations following 4 weeks of BT in young adults by conditioning the Hoffman reflex with transcranial magnetic stimulation. After training, facilitation of H-reflexes and motor-evoked potentials significantly decreased compared to the CG during stance perturbations on a platform. Since improved balance performance was negatively correlated with changes in cortical excitability while changes in the H-reflex were not, the authors argued that improvements in balance performance can be attributed to supraspinal adaptations. Studies examining cortical adaptations to BT in the elderly are scarce. However, recent studies investigating cortical plasticity following training in the elderly have supported the role of supraspinal plasticity following BT (Godde & Voelcker-Rehage, 2017; Schättin, Arner, Gennaro, & Bruin, 2016).

Although many studies have proven the effects of BT in older adults in recent years, clear dose-response relationships were continuously lacking. In an attempt to overcome this gap in the literature, a recent meta-analysis (Lesinski et al., 2015b) reported that the most effective improvements of BT versus controls were achieved with a training period of 11-12 weeks [weighted mean standardized mean difference between subjects ( $SMD_{bs}$ ) = 1.26], a frequency of three training sessions per week ( $SMD_{bs}$  = 1.20), a total number of 36-40 training sessions ( $SMD_{bs}$  = 1.39), and a 31-45 min duration for a single training session ( $SMD_{bs}$  = 1.19). These results may guide practitioners in the preparation of BT programs in older adults but have to be interpreted with caution, as the doses were indirectly compared across studies. Furthermore, there is still no feasible and valid method to detect the training intensity of BT.

In summary, BT is an effective means to improve motor performance in older adults and should be incorporated in fall-preventive exercise interventions, involving all components of balance control (i.e., static/dynamic steady-state, proactive, reactive). Based on the findings of studies that included unexpected perturbations and multi-task situations (Granacher, Muehlbauer, Bridenbaugh, Bleiker et al., 2010; Mynark & Koceja, 2002; Sakai, Shiba, Sato, &

Takahira, 2008; Silsupadol et al., 2009) it was argued that these types of BT may be particularly effective in promoting balance control during important balance-threatening situations of daily living (e.g., tripping, walking while talking).

### 2.3.2 *Resistance training in older adults*

In the literature, training protocols that aimed at improving muscle strength/power have interchangeably been referred to as “resistance training,” “strength training,” “weight training,” or “power training.” As the term ‘resistance training’ comprises specific methods of conditioning that involve a wide range of loads and training modalities, it will be used throughout this doctoral thesis.

The effects of resistance training (RT) have been extensively examined over the past three decades of research. Since the 1990s, it has become clearer that RT is a feasible and effective means to improve muscle strength in the elderly (Granacher, Muehlbauer, Zahner et al., 2011). With advanced knowledge about dose-response relationships, especially the feasibility and effects of RT with heavy loads [ $> 70$  % one repetition maximum (1RM)], training protocols have become more intense (Latham, Bennett, Stretton, & Anderson, 2004). Today, such high-intensity programs are well established. However, RT that involves exercises with high movement velocities have grown more and more pronounced in the scientific literature (Beijersbergen et al., 2016; Beijersbergen, Granacher, Gaebler, Devita, & Hortobágyi, 2017b), suggesting larger effects on explosive force production in the elderly (Granacher, Muehlbauer, Zahner et al., 2011).

Previous studies and systematic reviews have shown that RT in older adults is feasible and substantially improves measures of muscle strength/power (machine-based and clinical tests). The effects of RT on balance performance are contradictory (Liu & Latham, 2009). Regarding effects on the occurrence of falls, RT as a single intervention seems to have limited influence (Gillespie et al., 2012; Sherrington et al., 2016). In fact, Borde, Hortobágyi, and Granacher (2015) reported in a recent meta-analysis of 25 studies that RT substantially improved muscle strength (1RM) with a weighted mean effect size of 1.57 (95 % CI 1.20-1.94), indicating large effects compared to controls. Significant improvements of 1RM of the upper and lower extremities ranged from 3 to 106 %. Additionally, several studies proved that different RT protocols have an impact on muscle power performance in the elderly. For example, Fielding (2002) investigated the effects of a 16-week high- vs. low-velocity RT in elderly women (mean age 73 years). Both groups improved knee extensor 1RM strength (high velocity: 45



%, low velocity: 41 %). However, the high velocity group showed significantly larger improvements in leg press peak muscle power (97 %) compared to the low velocity group (45 %). For a review, see Granacher, Muehlbauer, Zahner et al. (2011). In addition to machine-based muscle strength/power tests, RT proved to be effective in enhancing performance in clinical muscle strength/power tests. These tests are important for the geriatric population, because they are feasible and easy to administer, even in home-based settings. In fact, a meta-analysis (Liu & Latham, 2009) revealed a large effect in favor of RT compared to inactive controls on timed chair rise performance (weighted mean SMD: 0.94, 95 % CI 0.38-1.49) and stair climbing performance (weighted mean SMD: 1.44, 95 % CI 0.37-2.51).

From a functional point of view, it is of interest whether adaptations following RT positively influence balance performance in older adults. Orr, Raymond, and Fiatarone Singh (2008) concluded in their systematic review that progressive RT as an isolated intervention is not consistently effective in improving balance in older adults. In only 22 % of all examined balance tests, significantly enhanced improvements compared to controls were reported. In contrast, a meta-analysis that investigated the effects of progressive RT compared to controls in older adults (Liu & Latham, 2009) found significantly enhanced performances in favor of RT for measures of dynamic steady-state balance (i.e., gait speed, 24 studies, mean difference: 0.08 m/s, 95 % CI 0.04-0.12) and proactive balance (e.g., TUG, 12 studies, mean difference: 0.69 s, 95 % CI 0.27-1.11).

Newer approaches also suggest that transfer effects are task-specific and that particularly high-velocity RT improved older adults' fast gait speed, but not habitual gait speed (Beijersbergen, Granacher, Gaebler, Devita, & Hortobágyi, 2017a). Additionally, Howe et al. (2011) extended these findings on static steady-state balance. Regarding improvements of single leg stance with eyes closed, progressive RT significantly improved standing time (mean difference: 1.64 s, 95 % CI 0.97-2.31). These results were not present for single leg stance with eyes opened and have to be interpreted with caution, as only three studies were identified that measured single leg stance after RT. Due to the heterogeneous results regarding transferability of RT gains to balance performance, it seems that RT and BT should be implemented complementarily (see Chapter 2.3.3). This is supported by meta-analyses that evaluated the effects of RT as a single exercise intervention on the rate of falls (Gillespie et al., 2012; Sherrington et al., 2016). RT as a single exercise intervention showed a non-significant effect on falls, with a mean reduction of 3 % in community-dwelling older people (incidence rate ratio: 0.97, 95 % CI 0.82-1.15) (Sherrington et al., 2016).

The underlying physiological mechanisms leading to functional improvements of RT in older adults have been attributed to muscle hypertrophy along with changes in the neuromuscular system. Regarding the age-related loss of muscle size, the data suggests that long-term RT to some extent can compensate particularly for the loss of muscle fiber size in old age (Aagaard et al., 2010; Haekkinen, 2003). A recently published meta-analysis showed that muscle mass increased with RT in older adults, but effects were small (weighted mean SMD: 0.42, 95 % CI 0.18-0.66). Increases in muscle mass ranged from 0.4 % to 21 %, depending on the measuring technique and variables assessed. Other reviews reported gains in muscle cross-sectional area and volume in the elderly, ranging from 5-12 % (Aagaard et al., 2010). Changes in muscle architecture with regard to an increased muscle fiber pennation angle (Morse, Thom, Mian, Birch, & Narici, 2007; Reeves, Narici, & Maganaris, 2004) as well as increased tendon stiffness (Reeves, Narici, & Maganaris, 2003) may also contribute to the enhanced muscle strength/power performance after RT in older adults. Additionally, several neural factors were discussed as potential mechanisms for the improvements of RT in the older population, including decreased antagonist coactivation (Haekkinen et al., 1998; Haekkinen, Kraemer, Newton, & Alen, 2001), improved coactivation of synergists (Haekkinen, 2003), increased magnitude of efferent neuromuscular activity (Haekkinen et al., 1998; Suetta et al., 2004), and an increased maximum motoneuron firing frequency (Kamen & Knight, 2004). For reviews, see Aagaard et al. (2010) and Haekkinen (2003).

Due to the heterogeneous training modalities of previous RT protocols, distinct recommendations were hard to derive. A meta-analysis on dose-response relationships of RT (Borde et al., 2015) revealed that a RT with the goal of increasing healthy older adults' muscle strength is characterized by a training period of 50-53 weeks, a training intensity of 70-79 % of the 1RM, a time under tension of 6 s per repetition, and a rest in between sets of 60 s. Selecting a training frequency of two sessions per week, a training volume of two to three sets per exercise, and a rest of 4.0 s between repetitions could also improve the efficacy of training (Borde et al., 2015). Dose-response relationships of high-velocity RT are lacking.

In summary, RT is an effective means to improve older adults' muscle strength/power and should be incorporated in fall-preventive exercise programs. Particularly high-velocity RT (power training) may be an effective method to enhance static and dynamic balance performance (Granacher, Muehlbauer, Zahner et al., 2011), which potentially improves the fall-preventive character of such programs.

### 2.3.3 *Potential benefits of enhanced trunk muscle performance in older adults*

As highlighted in Chapter 2.3.2, the effects of RT on balance performance are heterogeneous. The absence of such transfer effects may be partially explained by exercises implemented in previous RT as well as other fall-preventive exercise programs. Regarding the exercises implemented in such fall-preventive exercise programs, balance and/or lower extremity resistance exercises have predominantly been used (Granacher, Muehlbauer, Zahner et al., 2011; Liu & Latham, 2009). Since the mid-00s, particularly the lay literature has promoted the importance of trunk muscle strength (TMS) for the successful performance of everyday and sports-related activities, but also for preventive and rehabilitative purposes (Akuthota & Nadler, 2004). Consequently, researchers, mainly from the field of sports performance, have established a general understanding of the role of the trunk/core musculature. The core/trunk can be thought of as a muscular box, comprising the abdominal muscles in the front, paraspinal and gluteal muscles in the back, and the diaphragm and pelvic floor muscles as the top and bottom (Akuthota, Ferreiro, Moore, & Fredericson, 2008). According to Behm et al. (Behm, Drinkwater, Willardson, & Cowley, 2010), the core/trunk represents a kinetic link that facilitates the transfer of torque and angular momentum between the lower and upper extremities during the performance of activities of daily living, occupational tasks, and sports-related activities. Kibler et al. (Kibler, Press, & Sciascia, 2006) concluded that the core/trunk is especially important because it provides proximal stability for distal mobility by stabilizing the spine and pelvis. Studies have also tried to examine the importance of trunk muscle performance for the geriatric population. For example, there seems to be a significant association between TMS and static steady-state balance (single leg stance) as well as functional performance/balance test batteries (Short Physical Performance Battery, Berg Balance Scale) in community-dwelling older adults with a mean age of 76 years (Suri et al., 2009). Further, Hicks et al. (2005b) showed that trunk muscle composition predicts static and dynamic steady-state balance performance in adults aged 70-79 years. Three years later, participants with poor trunk muscle composition exhibited significantly reduced performance. Besides balance, trunk muscle composition also seems to be associated with hyperkyphotic posture in healthy community-dwelling older adults (Katzman et al., 2012). In terms of flexibility, Balogun et al. (Balogun, Olokungbemi, & Kuforiji, 1992) revealed that improvements in trunk muscle strength are significantly associated with spinal mobility, which decreases with age (Haemaelaenen, Suni, Pasanen, Malmberg, & Miilunpalo, 2006) and seems to be associated with poor mobility (Malmberg et al., 2002). Finally, Kasukawa et al. (2010) were able to

show that back extensor strength, lumbar kyphosis, and spinal mobility were significantly associated with the occurrence of falls in elderly subjects aged 60-92 years.

Findings from these previous cross-sectional studies suggest that measures of TMS are associated with spinal kyphosis as well as spinal mobility, and thus may modulate static/dynamic balance and falls in older adults. However, a systematic review of the associations between measures of TMS, balance, functional performance and falls in older adults revealed only small to medium correlations (Granacher et al., 2013). Since only six studies could be included in the review, and these being heterogeneous in terms of subjects and testing methodology, the authors classified their results as preliminary. Based on these preliminary findings, additional well-designed, cross-sectional studies are needed that investigate the relationship between measures of TMS and balance performance in healthy older adults. Further, associations between spinal mobility and balance performance have not yet been examined in the elderly. Clarification of relationships between these measures may help to develop the required specifically tailored exercise programs that are most effective in decreasing fall risk by improving balance and muscle strength/power in older adults.

#### *2.3.4 Combined balance and resistance training in older adults*

Despite the effects of BT and RT as single interventions, combined forms have been implemented in many studies throughout recent years (Ballard, McFarland, Wallace, Holiday, & Roberson, 2004; Bunout et al., 2005; Campbell et al., 1997; Cyarto et al., 2008a; Day et al., 2002; Freiburger et al., 2013; Gianoudis et al., 2014; Korpelainen, Keinänen-Kiukaanniemi, Heikkinen, Väänänen, & Korpelainen, 2006; Lord et al., 2003; Luukinen et al., 2007; Park, Kim, Komatsu, Park, & Mutoh, 2008; Seco et al., 2013; Smulders et al., 2010; Suzuki et al., 2004; Zhuang et al., 2014). Results suggest that a CRT has positive effects on both balance and muscle strength/power performance in older adults. Campbell et al. (1997) were among the first to examine the effects of CRT in people aged 80 years and older living in the community. After a 6-month CRT program, participants of the IG showed significantly enhanced balance (i.e., 4-test balance score) and muscle power (i.e., CST) performance compared to controls. After a one year follow-up, the number of falls was significantly reduced in the CRT group compared to the CG (rate of falls per person annually CRT: 0.87; rate of falls per person annually CG: 1.34; difference: 0.47, 95 % CI 0.04-0.90). This is in line with a meta-analysis that reported the effects of various interventions (e.g., BT, RT, multifactorial exercise interventions including CRT, vitamin D supplementation) on risk of falling and rate of falls.

Overall, group-based exercise interventions containing multiple components of exercises (80 % of the studies involved CRT) achieved a statistically significant reduction in the rate of falls (pooled rate ratio: 0.71, 95 % CI 0.63-0.82; 16 studies; 3,622 participants) and the risk of falling (pooled risk ratio: 0.85, 95 % CI 0.76-0.96; 22 studies; 5,333 participants). Thus, CRT is a promising approach that has the potential to improve balance and muscle strength/power in healthy elderly individuals. However, previous studies are limited in as much as they assessed only specific measures of balance and/or muscle strength/power performance (Ballard et al., 2004; Bunout et al., 2005; Day et al., 2002; Freiberger et al., 2013; Gianoudis et al., 2014; Luukinen et al., 2007; Park et al., 2008; Seco et al., 2013; Smulders et al., 2010; Suzuki et al., 2004; Zhuang et al., 2014) or included pathological participants (Campbell et al., 1997; Freiberger et al., 2013; Gianoudis et al., 2014; Korpelainen et al., 2006; Lord et al., 2003). Further, studies are heterogeneous in terms of modalities of exercise supervision (i.e., supervised, unsupervised, combination of supervised and unsupervised).

There is no RCT that investigated the effects of both supervised and unsupervised CRT versus inactive controls on all different components of balance control (i.e., static/dynamic steady-state, proactive, and reactive balance) as well as muscle strength/power in healthy older adults. Future studies should evaluate these comprehensive effects of CRT in healthy older adults and provide the most effective modalities (e.g., amount of exercise supervision) to implement such fall-preventive programs for preferably large populations.

#### **2.4 Modalities of supervision in balance and resistance training in older adults**

In Chapter 2.3, the substantial effects of BT/RT on measures of balance, muscle strength/power, and falls were documented. Previous RCTs and reviews also established dose-response relationships for BT and RT. However, there is a gap in the literature with regard to the programs being delivered with or without supervision. Fall-preventive exercise programs including BT and/or RT have been implemented as supervised training programs (SUP; some supervised programs were delivered at home), unsupervised training programs (UNSUP; mostly home-based), or a combination of SUP and UNSUP (Christie, 2011; Freiberger et al., 2013; Gillespie et al., 2012; Howe et al., 2011). In a systematic review and meta-analysis on exercise for fall prevention, Sherrington et al. (2016) included 69 studies irrespective of setting (facility-based, home-based) or amount of supervision (minimally supervised, fully supervised, or a combination of supervised and unsupervised sessions). Overall, studies reduced the rate of falling in community dwellers by 21 % (pooled rate ratio: 0.79,

95 % CI 0.73-0.85). A distinction, as to whether UNSUP versus SUP were equally effective in preventing falls is not possible based on these findings. Yet, recent recommendations have hypothesized that fall prevention exercises in group- and home-based settings are equally effective (Gillespie et al., 2012) and may be undertaken independently of location (Sherrington et al., 2016). Home-based interventions may have the potential to include a large number of older adults in fall-preventive exercise programs, as the barriers to participation are lowered. This could facilitate a widespread implementation of such programs. However, in view of the recent recommendations that home- and facility-based interventions are equally effective, it is of utmost importance to address the role of supervision in a first step. Thereby, the effectiveness of unsupervised compared with supervised exercise interventions could be resolved and practitioners could directly apply the results in clinical practice. The following chapters will provide a brief overview of modalities of supervised (Chapter 2.4.1) and unsupervised BT and RT interventions (Chapter 2.4.2) in older adults, and finally present studies targeting the comparison of SUP and UNSUP (Chapter 2.4.3).

#### *2.4.1 Supervised balance and/or resistance training in older adults*

In this doctoral thesis, the term ‘supervised’ refers to the attendance of a training session by an instructor supervising the execution of exercises (e.g., to give instructions on how exercises are performed correctly, to establish appropriate intensity/progression). The majority of BT and/or RT interventions in older adults have been implemented under supervision, as documented in systematic reviews and meta-analyses (Gillespie et al., 2012; Howe et al., 2011; Liu & Latham, 2009). Most of the fully supervised interventions were delivered in groups (i.e., gym-/facility-based), a smaller number as individually supervised interventions (partly in home environments) (Howe et al., 2011; Liu & Latham, 2009). The amount of supervision in the fully supervised interventions varied substantially between studies, ranging from one to three supervised sessions per week with training periods of four weeks to 12 months (Howe et al., 2011). The supervisors were fitness instructors, exercise physiologists, sports scientists, physical therapists, physiotherapists, researchers, and nurses (Campbell et al., 1997; Howe et al., 2011; Liu & Latham, 2009). However, a large number of studies did not report on the background of the supervisors (Howe et al., 2011).

The effects of supervised BT and/or RT on measures of balance performance (Howe et al., 2011) and muscle strength/power performance (Liu & Latham, 2009) have been proven by many studies. For example, Zhuang et al. (2014) investigated the impact of a 12-week (most

frequently used duration in SUP) supervised CRT on measures of balance and leg strength in elderly subjects aged 60-80 years. Significant improvements in favor of CRT compared to an inactive CG were found for measures of dynamic steady-state balance (e.g., gait speed,  $SMD_{bs}$ : 0.95), proactive balance (e.g., TUG,  $SMD_{bs}$ : 0.92), and muscle strength (e.g., isometric muscle strength of knee flexors,  $SMD_{bs}$ : 1.28; 30s CST,  $SMD_{bs}$ : 2.64). Positive effects of supervised group-based exercise interventions on falls and risk of falling have been convincingly reported in a Cochrane review by Gillespie et al. (2012) (see also chapter 2.3.3).

#### 2.4.2 *Unsupervised balance and/or resistance training in older adults*

Although the majority of previous BT and/or RT interventions in the elderly were supervised, several studies implemented unsupervised training protocols (for reviews see Gillespie et al., 2012; Howe et al., 2011; Liu & Latham, 2009).

To the best of the author's knowledge, each of these studies implemented some kind of supervision (e.g., booster visits to explain exercises, visits every 3-4 weeks during the intervention, phone calls) in their training protocols, which makes it difficult to define the term 'unsupervised'. In the literature, some authors used the terms 'home-based' and 'unsupervised' interchangeably. This is misleading, as 'home-based' refers to the setting and not to the delivery method. In addition, there are studies that implemented a 'supervised home-based' intervention (e.g., Mangione, Craik, Tomlinson, & Palombaro, 2005). Thus, the author suggests using the terms supervised/unsupervised if the goal is to examine the role of the attendance of an exercise instructor. With regard to a clear distinction between supervised and unsupervised protocols, we propose a ratio dividing the number of supervised training sessions by the total number of training sessions. For a detailed explanation, see Publication IV. Here, a cut-off describing unsupervised programs is suggested, considering the fact that almost every so-called 'unsupervised' exercise intervention contains at least a minimal amount of supervision. Training protocols of unsupervised BT/RT interventions varied substantially regarding the number of unsupervised sessions per week (2 to 7 sessions/week) and training period (6 to 26 weeks) (Clemson et al., 2012; Gillespie et al., 2012; Howe et al., 2011; Liu & Latham, 2009). In addition, many interventions included regular phone calls. A smaller number of studies applied exercise booklets or video instructions. All of the identified unsupervised exercise interventions took place in the subjects' homes.

The applied unsupervised BT and/or RT interventions seem to have the potential to improve measures of balance and muscle strength/power performance (Howe et al., 2011; Liu

& Latham, 2009). For example, Clemson et al. (2012) applied a lifestyle-integrated approach containing balance and resistance exercises in community-dwelling older adults aged 70 years or older. The prescribed exercises (e.g., squatting instead of bending during household activities; tandem stance while working in the kitchen) had to be performed whenever possible during each day for a period of six months. After the intervention period, the lifestyle intervention significantly improved static/dynamic steady-state balance (i.e., five-level balance hierarchy, tandem walk time) and muscle strength (i.e., right and left ankle) compared to an inactive CG (effect sizes: 0.40-0.63).

As described above, previous meta-analyses have not elucidated the effects of unsupervised BT/RT on falls, because the analyses referred to the setting of the programs (i.e., home-based) and contained both SUP and UNSUP interventions as well as combinations of both (Gillespie et al., 2012; Sherrington et al., 2016). As the analyses did not distinguish between SUP and UNSUP interventions, the home-based programs in these analyses contain a valuable amount of UNSUP interventions. However, based on these findings, recommendations state that fall-preventive exercise interventions can be conducted in either a group- or home-based setting (Gillespie et al., 2012; Sherrington et al., 2016). This may suggest equal effects of supervised and unsupervised home-based programs. It is therefore important to address the inconsistencies regarding supervised versus unsupervised BT/RT interventions.

What may be the benefits of implementing unsupervised home-based BT and/or RT interventions? Evidence in support of the hypothesis that unsupervised home-based interventions are equally effective compared to supervised interventions may increase the number of older adults participating in fall-preventive exercise programs, as many elderly persons do not have the ability (e.g., poor health status) or motivation to participate in supervised facility-based programs (Cohen-Mansfield et al., 2003). In fact, findings from a recent study (Franco et al., 2015) indicate that older adults with a history of falls prefer to participate in exercise programs that can be conducted at home. Two hundred and twenty community-dwelling Australian adults aged 60 years or older with a history of falls were asked about the relative values they attach to different attributes of exercise (i.e., exercise type, time spent on exercise per day, frequency, transport type, travel time, costs, reduction of fall risk, improvement in activities of daily living). Participants had to select the attribute that was most likely to be associated with a program they wanted to participate in and the attribute that was least likely to be associated with such a program. Interestingly, the attributes of exercise programs with the highest utility values (that were most likely associated with a good program) were connected



neither with the health outcomes nor with the exercise type, but were “home-based exercise” and “no need to use transport”. Attributes with the lowest utility (that were least likely to be associated with good programs) were “travel time of 30 minutes or more” and “out-of-pocket costs of AUD50 per session.” Other studies referred to the high level of perceived participant autonomy during unsupervised home-based exercise interventions as a trigger for high adherence to such programs (Simek et al., 2015). Another potential benefit of unsupervised home-based exercise is the cost-effectiveness of such programs (Davis et al., 2010). Since this doctoral thesis primarily addresses physiological factors of BT and RT, cost-related aspects are not debated. Facilitating participation and reducing the costs of exercise interventions are important issues. However, the physiological effectiveness of an exercise intervention in terms of the potential to mitigate intrinsic fall risk factors is of at least the same significance and must be clarified first.

#### *2.4.3 Supervised versus unsupervised balance and resistance training in older adults*

The indirect comparison of studies examining the effects of either SUP or UNSUP with inactive control groups is afflicted with bias. Consequently, there is need of studies that directly compare SUP and UNSUP within one study, preferably with a RCT approach.

Chapter 2.3.3 highlighted that particularly the combination of BT and RT (CRT) seems to be a promising approach in terms of mitigating intrinsic fall risk factors. Previous studies that examined the effects of SUP compared to UNSUP CRT in the elderly provided only preliminary evidence, as they were heterogeneous in terms of results and/or used limited methodological approaches (Almeida et al., 2013; Cyarto et al., 2008b, 2008a; Donat & Oezcan, 2007; Helbostad et al., 2004a; Tuunainen et al., 2013; van Roie et al., 2010; Wu et al., 2010). Regarding improvements in balance and muscle strength performance, some studies indicated a superiority of SUP for specific measures (Cyarto et al., 2008b; Donat & Oezcan, 2007; van Roie et al., 2010; Wu et al., 2010), while others did not (Almeida et al., 2013; Helbostad et al., 2004a, 2004b).

Studies indicating a superiority of SUP versus UNSUP in specific performance measures are not consistent. Regarding studies measuring balance performance, two studies detected a superiority in terms of the effects on static steady-state balance, but not on proactive balance (Cyarto et al., 2008b; Donat & Oezcan, 2007), while others found superior effects of SUP for both static steady-state and proactive balance (Wu et al., 2010). Studies measuring the effects of SUP versus UNSUP on muscle strength found no differences (Almeida et al., 2013; Cyarto

et al., 2008a; van Roie et al., 2010), while others indicate a superiority of SUP (Watson, Weeks, Weis, Horan, & Beck, 2015). Further, previous studies are methodologically limited, since they assessed specific components of balance performance only (mono-method bias; e.g., static but not dynamic, proactive, and reactive balance) (Tuunainen et al., 2013; Watson et al., 2015) or implemented incomparable training protocols (e.g., varying volumes) in SUP and UNSUP (Helbostad et al., 2004a; Tuunainen et al., 2013). Other studies did not sufficiently report the modalities of supervision. Due to the heterogeneous and inconsistent results with tendencies, at least for balance variables, indicating a superiority of SUP versus UNSUP after CRT, there is a need for studies that provide a clearer and more comprehensive view on the effects of exercise supervision in older adults. To the best of the author's knowledge, no study has examined the effects of a supervised compared to unsupervised CRT and inactivity (control group) on static/dynamic steady-state, proactive, and reactive balance as well as lower extremity muscle strength/power in healthy older adults. Further, studies evaluating detraining effects following CRT are scarce and report contradictory findings (Carvalho, Marques, & Mota, 2009; Helbostad et al., 2004a; Seco et al., 2013). In order to document the robustness of possible training-related adaptations, information on detraining effects is required. With regard to factors that impair exercise participation, such as high susceptibility to diseases, injuries, family commitments, or even extended travels, particularly older people may be prone to longer periods of training cessation.

Despite the heterogeneity of studies, results from original work indicate that supervised rather than unsupervised BT and/or RT causes greater effects on balance and muscle strength/power in older adults. In addition to the lack of comprehensive RCTs, there is a gap in the literature regarding the aggregation of original work. A systematic comparison of the two delivery methods (i.e., SUP, UNSUP) in terms of a systematic review and meta-analysis could provide the most reliable evidence, because it combines the results of independent studies in estimating the size of the effect in the population (Burns et al., 2011; Ellis, 2011). Previous reviews dealing with the issue compared home- and/or group-based exercise interventions with inactive controls (Gillespie et al., 2012; Hill, Hunter, Batchelor, Cavalheri, & Burton, 2015), without directly comparing the underlying exercise effects in SUP and UNSUP (i.e., aggregation of studies that implemented both SUP and UNSUP). For example, Hill et al. (2015) evaluated in a systematic review and meta-analysis the impact of individualized home-based exercise programs on measures of physical activity, balance, and muscle strength in older adults aged 60 years or over. Individualized home-based exercise programs significantly increased

physical activity (i.e., physical activity scale for the elderly; mean difference: 15.88, 95 % CI 7.80-27.02), proactive balance (i.e., FRT; mean difference: 1.57, 95 % CI 0.37-2.76), and muscle strength (i.e., knee extensor strength; SMD: 0.16, 95 % CI 0-0.33) compared to controls (Hill et al., 2015). However, conclusions regarding the effects of unsupervised training may be biased, because some of the home-based programs were extensively supervised. In another meta-analysis, Gillespie et al. (2012) examined, among others, the effects of home- and group-based exercise interventions (mainly CRT) on fall risk and fall rate. Both home-based and group-based interventions achieved statistically significant reductions regarding rate of falls (home-based: pooled rate ratio: 0.68, 95 % CI 0.58-0.80; 7 studies; 951 participants; group-based: pooled rate ratio: 0.71, 95 % CI 0.63-0.82; 16 studies; 3,622 participants) and risk of falling (home-based: pooled risk ratio: 0.78, 95 % CI 0.64-0.94; 6 studies; 714 participants; group-based: pooled risk ratio: 0.85, 95 % CI 0.76-0.96; 22 studies; 5,333 participants) compared to inactive controls. This analysis does not allow for a direct comparison of home- and group-based interventions. Furthermore, the home-based interventions in the meta-analysis of Gillespie et al. (2012) are not equivalent to unsupervised interventions, as some comprised a substantial amount of supervision (e.g., Lin, Wolf, Hwang, Gong, & Chen, 2007; Robertson, Devlin, Gardner, & Campbell, 2001).

Other systematic reviews and meta-analyses evaluated the effects of home- versus center-based exercise interventions in older patients with severe diseases [i.e., cardiovascular disease, chronic obstructive pulmonary disorder, peripheral vascular disease (Ashworth, Chad, Harrison, Reeder, & Marshall, 2005); intermittent claudication (Fokkenrood et al., 2013), myocardial infarction, angina, heart failure, or revascularization (Taylor et al., 2015)].

For example, Taylor et al. (2015) aggregated RCTs that compared home- and facility-based forms of cardiac rehabilitation. After 12-months, no difference was seen between home- and facility-based cardiac rehabilitation in health-related quality of life (e.g., EQ-5D questionnaire). The authors concluded that both programs improved quality of life to a similar extent. In contrast, other systematic reviews found that facility-based programs were superior compared to home-based ones if the goal was to improve walking distance and time to claudication. In this regard, Ashworth et al. (2005) assessed the effectiveness of home- versus facility-based physical activity programs (i.e., all types of exercise) in patients aged 50 years or older with one or more risk factors/cardiovascular diseases (e.g., ischemic heart disease, diabetes, chronic obstructive pulmonary disease, peripheral vascular disease). In patients with peripheral vascular disease (i.e., intermittent claudication), facility-based programs improved maximal

walking distance and time to claudication (measured on a treadmill) to a greater extent than home-based programs. According to these results, Fokkenrood et al. (2013) showed that SUP (mainly walking and resistance training of the lower extremities) compared to UNSUP significantly improved walking distance in patients with intermittent claudication. Weighted mean effect sizes were medium, with values of 0.69 (95 % CI 0.51-0.86) and 0.48 (95 % CI 0.32-0.64) at three and six months, respectively.

Due to the methodological limitations of previous systematic reviews and meta-analyses (i.e., indirect comparisons of so-called supervised and unsupervised exercise interventions), as well as heterogeneous results in specific clinical populations, it seems appropriate and timely to fill this gap in the literature by conducting a meta-analysis of the effectiveness of supervised compared to unsupervised BT and/or RT in healthy older adults. Additionally, no previous review has determined the dose-response relationships of exercise supervision on balance and muscle strength/power outcomes in this population. Dose-response relationships are indispensable for providing evidence-based recommendations for practitioners and therapists.

### **3. Research hypotheses**

The preceding paragraphs presented a review of age-related changes in motor performance (Chapter 2.1), described important fall risk factors (Chapter 2.2), and provided an overview of previous BT and/or RT interventions in older adults (Chapter 2.3). Finally, the modalities of supervision (i.e., attendance of an exercise instructor) in such fall-preventive exercise interventions were discussed (Chapter 2.4). Based on this literature review, several gaps in the literature regarding factors potentially influencing the effects of BT and RT in older adults have been identified. The following deductions and research hypotheses of this doctoral thesis are based on the theoretical analysis in Chapter 2.

#### *Deduction 1*

There is preliminary evidence that trunk muscle strength and spinal mobility may modulate balance performance in older adults.

#### *Hypothesis 1*

Measures of trunk muscle strength and spinal mobility are significantly associated with measures of static/dynamic steady-state, proactive, and reactive balance in healthy older adults (Publication I).

#### *Deduction 2*

There is growing evidence that particularly the combination of balance and resistance training (CRT) is able to improve balance and muscle strength/power in the elderly population. It has been separately reported that supervised and unsupervised CRT has resulted in enhanced performance in specific tests of balance and muscle strength.

#### *Hypothesis 2*

Compared to an inactive control group, a 12-week CRT (supervised and unsupervised) in healthy older adults will result in significant improvements in primary (i.e., static/dynamic steady-state, proactive, reactive balance; muscle power) and secondary outcome variables (i.e., falls efficacy, cognitive function, quality of life, and body composition) (Publications II and III).

*Deduction 3*

In addition to *Deduction 2*, there is only preliminary evidence regarding the effects of supervised compared to unsupervised CRT, as previous longitudinal studies were heterogeneous and methodologically limited. Results of previous randomized controlled trials indicate a superiority of supervised exercise interventions.

*Hypothesis 3*

Compared with a 12-week unsupervised CRT, a 12-week supervised CRT in healthy older adults will cause larger performance enhancements in all primary (i.e., balance, muscle power) and secondary outcome variables (i.e., falls efficacy, cognitive function, quality of life, and body composition) (Publications II and III).

*Deduction 4*

There is a lack of evidence regarding detraining effects following CRT, because the few available studies have reported contradictory findings.

*Hypothesis 4*

Training-related improvements following a 12-week CRT in healthy older adults will remain above baseline values after 12 weeks of detraining for both supervised and unsupervised training groups (Publications II and III).

*Deduction 5*

There is a gap in the literature regarding aggregation of the effects of supervised versus unsupervised balance training, resistance training, and the combination of both. Previous systematic reviews on clinical populations provide preliminary evidence that supervised exercise interventions may be superior to unsupervised exercise interventions.

*Hypothesis 5*

Supervised exercise programs are superior to unsupervised exercise programs for improving healthy older adults' balance and muscle strength/power performance (Publication IV).

*Deduction 6*

In addition to *Deduction 5*, there is a lack of evidence regarding the impact of exercise supervision in the form of dose-response relationships on balance and muscle strength/power outcomes in healthy older adults.

*Hypothesis 6*

The positive effects of supervised compared to unsupervised balance and/or resistance training on balance and muscle strength/power performance in healthy older adults will be larger in studies that implement a larger amount of supervision (Publication IV).

## **4. Materials and methods**

The following chapter briefly summarizes the characteristics of the participants, the apparatus and questionnaires, the training protocol, and the statistical analyses. The methodological approach of this doctoral thesis was based on the deduced research hypotheses. Detailed information on materials and methods are provided in the respective publications (see Publications I, II, III, and IV).

### **4.1 Participants**

All study participants of Publications I and III were healthy older adults (aged 63-80 years) without any known neurological, musculoskeletal, or orthopedic disorders that might have affected their ability to perform the applied tests or training protocols. Further, only cognitively healthy older adults were eligible to participate in the studies. None of the subjects of Publications I and III had experience with the applied tests or previously participated in a regular BT and/or RT program. All subjects gave their written informed consent prior to the beginning of the study. The studies were approved by the local ethics committees and conducted according to the latest version of the Declaration of Helsinki. Detailed information on participants' characteristics is presented in the "Methods" sections of the respective publications (see Publications I, II, III, and IV).

### **4.2 Assessment tools**

The assessments were conducted in the laboratories of the Mooswaldklinik Freiburg, Germany (cooperation partner of the Institute of Sport and Sport Science, Albert-Ludwigs-University Freiburg, Germany; Publication I) and in the biomechanical laboratory of the Division of Training and Movement Science at the University of Potsdam, Germany (Publication III). Measurements primarily included the assessment of static/dynamic steady-state, proactive, and reactive balance as well as trunk/lower extremity muscle strength/power. Detailed information on the testing procedures is given in Publications I, II, and III.

#### *4.2.1 Assessment of static steady-state balance*

Participants' static steady-state balance was assessed with two measurement systems. Publication I used a balance platform (GKS 1000; IMM, Mittweida, Germany). The balance platform contains four uniaxial sensors measuring displacements of the center of pressure (CoP). For experimental testing, participants were asked to perform a tandem stance on a balance pad.



Subjects had to stand upright, hands placed on hips and gaze fixated on a nearby wall. Data were acquired for 30 s at a sampling rate of 40 Hz. Summed displacements (cm) of the CoP in anterior-posterior (AP) and mediolateral (ML) directions were used for further evaluation. Publication III used the modified Romberg Test (ROM) while standing on a three-dimensional force plate (Leonardo 105 Mechanograph®; Novotec Medical GmbH, Pforzheim, Germany). Participants stood in an upright position on a balance pad for 30 s without shoes, feet closed, arms fully extended in front of the body with palms facing upwards, and eyes closed. Testing was terminated if participants opened their eyes, or moved their arms or feet in order to achieve stability. In case of a failed attempt, an additional trial was provided. Achieved standing time (s) and the path velocity (mm/s) of the center of force (CoF) were assessed. Previously, a high test-retest and interrater reliability has been shown for the modified ROM (Granacher, Muehlbauer et al., 2014). Detailed descriptions of these testing procedures can be found in Publications I, II, and III.

#### 4.2.2 *Assessment of dynamic steady-state balance*

Dynamic steady-state balance was tested with the OptoGait® System (Microgate, Bolzano, Italy). The OptoGait® System is an opto-electrical 10-meter walkway, consisting of transmitting and receiving bars. Each bar is 1 m in length and contains 100 LEDs, which continuously transmit to an oppositely positioned bar. Any break in this continuous connection can be measured and timed. Spatiotemporal gait data were registered at 1,000 Hz. Participants were asked to walk at their habitual walking speed wearing their own footwear. To allow sufficient distance for acceleration and deceleration, each trial was initiated and terminated a minimum of 2 m off the walkway. Various measures of dynamic steady-state balance were calculated across studies. In Publication I, stride time [time (s) between the first contacts of two consecutive footfalls of the same foot], stride length [distance (cm) between successive heel contacts of the same foot], and stride velocity (distance in meters covered per second during one stride) were computed. In Publication III, stride length and stride velocity as well as the corresponding coefficients of variation [CV; standard deviation (SD)/mean  $\times$  100] were analyzed. Publication III additionally assessed dynamic steady-state balance under dual task conditions. For the dual task condition, participants had to recite out loud subtractions. One test trial was performed for each condition. The OptoGait® System demonstrated high test-retest reliability (Lee et al., 2014) as well as high discriminant and concurrent validity (Lienhard, Schneider, &

Maffioletti, 2013). Detailed information on this procedure can be found in the appendix (Publications I, II, and III).

#### 4.2.3 *Assessment of proactive balance*

Proactive balance was measured using the Functional Reach Test (FRT; Publication III) (Duncan, Weiner, Chandler, & Studenski, 1990) and the Timed Up and Go Test (TUG; Publications I and III) (Podsiadlo & Richardson, 1991). The FRT measures the ability to reach forward while maintaining a fixed base of support in the standing position. Subjects stood with their feet shoulder width apart on a force plate (Leonardo 105 Mechanograph<sup>®</sup>) and reached forward with their outstretched dominant arm as far as they could. Three tests of 12 s were performed. Maximal reach distance (cm) and the path velocity (mm/s) of the CoF were assessed. The FRT proved to be reliable (Duncan et al., 1990) and valid (Newton, 2001). For the TUG, participants had to stand up from a chair (height: 46 cm), walk 3 m at their habitual walking speed, turn around and sit down again. A stopwatch was started at the command ‘ready-set-go’ and stopped as the participant sat down. Time was recorded to the nearest 0.01 s. After verbal instructions regarding the procedure, two test trials were performed. The TUG showed excellent test-retest reliability in older adults (Podsiadlo & Richardson, 1991). More detailed descriptions of these testing procedures can be found in Publications I, II, and III.

#### 4.2.4 *Assessment of reactive balance*

To test reactive balance, a ML perturbation impulse was applied while participants stood on a two-dimensional balance platform (Publications I and III: Posturomed, Haider Bioswing, Pullenreuth, Germany). The platform was free to move in the transversal plane. Before the beginning of the experiment, the platform was magnetically fixed 2.5 cm from the neutral position in the ML direction. Subjects were asked to stand on the platform in a narrow step stance, hands placed on their hips, and gaze fixated at the nearby wall. The assessor applied the perturbation impulse by unexpectedly detaching the magnet. Participants’ task was to damp the oscillating platform and stand as still as possible over a period of 10 s. Three test trials were performed. Summed oscillations (cm) of the platform in ML and AP directions were assessed by means of a 2D-potentiometer which was mounted to the platform. The signal of the potentiometer ( $^{\circ}$ ) was differentiated, rectified, and integrated. The mechanical constraints and the reliability of the system were described elsewhere (Mueller, Guenther, Krauss, & Horstmann,

2004). Detailed descriptions of this testing procedure can be found in Publications I, II, and III.

In Publication III, reactive balance was additionally assessed using the clinical PRT (Jacobs, Horak, van Tran, & Nutt, 2006). The PRT rates the postural response to a sudden perturbation. Subjects were asked to stand barefooted in comfortable stance with eyes opened. The examiner placed his hands on the subject's scapulae and participants had to push backward against his palms. When participants' shoulders and hips moved to a stable position just behind the heels, the examiner unexpectedly removed his hands, forcing the participants to take at least one step backward to regain balance. The quality of the recovery was rated according to the following scale: 0 = 1 step, 1 = 2–3 small steps with independent recovery, 2 =  $\geq 4$  steps with independent recovery, 3 = steps with assistance for recovery, 4 = fall or unable to stand without assistance. Three test trials were conducted. The PRT proved to be reliable and valid (Jacobs et al., 2006). Detailed information on this testing procedure can be found in Publications II and III.

#### *4.2.5 Assessment of spinal mobility*

Spinal mobility was determined using the MediMouse<sup>®</sup> system (Lucamed International GmbH, Bad Säckingen, Germany), a hand-held, computer-assisted electromechanical device for measuring spinal curvature in various postures (Seichert, Baumann, Senn, & Zuckriegel, 1994). The device was slowly moved along the midline of the spine, from the spinous process of C7 to the top of the anal crease (approximately S3). Before testing, these landmarks were palpated and marked on the skin surface. Tests were performed in four positions which included maximal extension, maximal flexion, and maximal lateral flexion to the left/right side. Angles ( $^{\circ}$ ) for the range of motion in the sagittal plane (maximal extension to flexion) and in the coronal plane (maximal left to right flexion) were determined and used as outcome measures. ICC values were calculated for spinal mobility in the sagittal (ICC = 0.85) and the coronal plane (ICC = 0.85). Additionally, the MediMouse<sup>®</sup> system demonstrated acceptable validity in adults (Guermazi et al., 2006). Further information on this testing procedure is provided in Publication I.

#### *4.2.6 Assessment of trunk muscle strength*

Trunk muscle strength was measured using NORSK trunk testing machines (NORSK, Ringsheim, Germany) that allowed the analysis of trunk flexion, trunk extension, trunk rotation in

transversal plane (right, left), and lateral trunk bending (right, left) (Paalanne et al., 2009). We assessed maximal isometric strength, defined as the maximal voluntary strength (i.e., peak value of the force-time curve [Nm]) determined under isometric conditions. Participants were tested in a sitting position, with thorax and pelvis firmly fixed by straps or cushions. Three maximal isometric contractions lasting 3–4 s were performed in each direction of movement. Strength tests were conducted in a counterbalanced order with a rest of 1 min between the single tests. Bak et al. (Bak, Anders, Bocker, & Smolenski, 2003) reported excellent inter- and intra-session reliability of the NORSK machines. In addition, intraclass correlation coefficients (ICC) were calculated for maximal isometric trunk muscle strength ranging from 0.89 to 0.96. Detailed information on this testing procedure is presented in Publication I.

#### 4.2.7 Assessment of lower extremity muscle strength/power

Lower extremity muscle strength/power was assessed using the Chair Stand Test (CST) while standing on a force plate (Leonardo 105 Mechanograph<sup>®</sup>) (Csuka & McCarty, 1985) and the Stair Ascent and Descent Test (SADT) (Tiedemann et al., 2008). To perform the CST, subjects were asked to sit on a chair with arms folded across the chest. After an acoustic signal, participants had to stand up (i.e., upright position) and sit down (i.e., touch chair with buttocks) five times as quickly as they could. The time (s) from the initial to the final seated position was measured with the force plate and the associated software to the nearest 0.01 s and used as outcome. Additionally, the average maximum power per kilogram body weight ( $P_{\max}$  [W/kg]) of the five sit-to-stand cycles was computed. Three test trials were conducted. The CST demonstrated excellent test-retest reliability as well as a predictive validity for falls (Tiedemann et al., 2008). Further information on this testing procedure is given in Publications II and III.

For the SADT, participants were asked to ascend and descent an eight-stair flight (stair height: 17.1 cm) at a fast but safe velocity. Time for ascending and descending the stairs was recorded separately with a stopwatch to the nearest 0.01 s. Timing for the Stair Ascent Test (SAT) began when the participant lifted the foot off the ground and was terminated when both feet were placed on the eighth step. Timing for the Stair Descent Test (SDT) started when the subject lifted the foot off the eighth step and stopped when both feet reached ground level. Additionally, stair climb power (W/kg) was calculated using the formula:  $power = force \times velocity$  (Bean, Kiely, LaRose, Alian, & Frontera, 2007). One test trial was performed. The SADT showed good test-retest reliability as well as a predictive ability for falls (Tiedemann et

al., 2008). Additional information regarding SADT testing procedure is presented in Publications II and III.

#### *4.2.8 Assessment of handgrip strength*

For baseline assessment in Publication III, handgrip strength (kg) was measured using a Jamar hand dynamometer (Sammons Preston Inc., Bolingbrook, Ill., USA). Subjects had to sit with both arms parallel to the body, holding the device in their dominant hand. After the command 'ready-set-go', subjects had to continuously increase their grip until maximal force was reached.

#### *4.2.9 Assessment of body composition*

A noninvasive bioelectrical impedance analysis was conducted, using an eight-electrode impedance meter (InBody 720, BioSpace, Seoul, Korea). In order to measure impedance of arms, trunk, and legs, alternating currents of 100 and 500  $\mu$ A at frequencies of 1, 5, 50, 250, 500, and 1,000 kHz were applied. Body mass (kg), body mass index ( $\text{kg}/\text{m}^2$ ), total body water (liters), lean tissue mass of the legs (kg), and total skeletal muscle mass (kg) were assessed and used as secondary outcomes in Publication III. Subjects stood barefoot on the device and placed their feet on the appropriate electrodes. They additionally held electrodes in both hands and abducted arms to approximately 40°. The InBody 720 proved to be a valid estimator of lean body mass in men and women ( $R^2 = 0.52-0.95$ ) (Anderson, Erceg, & Schroeder, 2012). A more detailed description of this testing procedure can be found in Publications II and III.

#### *4.2.10 Questionnaires*

Questionnaires were applied for baseline assessment in Publications I and III (i.e., Mini Mental State Examination, Clock Drawing Test, and Freiburg Questionnaire of physical activity) and as secondary outcome measures in Publication III (i.e., Falls Efficacy Scale - International, Digit Symbol Substitution Test, and World health organization quality of life - bref). Detailed descriptions of the questionnaires are provided in Publications I and II.

##### *Mini Mental State Examination*

The Mini Mental State Examination (MMSE) is a brief screening battery for the assessment of executive function that separates patients with cognitive disturbance from those without such disturbance (Folstein, Folstein, & McHugh, 1975). A cutoff-score of  $< 24$  was used to

detect cognitive impairment at baseline (Lopez, Charter, Mostafavi, Nibut, & Smith, 2005). The scores of the MMSE showed high test-retest reliability as well as good concurrent validity with the Wechsler adult intelligence scale (Folstein et al., 1975).

#### *Clock Drawing Test*

The Clock Drawing Test (CDT) is a test for detecting cognitive deficits (Manos & Wu, 1994). Subjects had to draw a clock in a given circle of 10 cm in diameter and complete it with all the numbers and hands. Afterwards, they were asked to write down the time in digital form. The test was used to discriminate between a pathological and normal test performance at baseline. The inter-rater reliability was shown to be high ( $r = 0.91$ ) (Thalmann et al., 2002). Cross-correlation with the MMSE revealed a correlation coefficient of  $r > 0.50$  (Shulman, 2000).

#### *Freiburg Questionnaire of Physical Activity*

Physical activity (hours/week) was assessed using the Freiburg Questionnaire of Physical Activity (FQoPA) (Frey, Berg, Grathwohl, & Keul, 1999). Participants were asked to report the amount of time spent in everyday activities as well as sport and recreational activities. The FQoPA demonstrated good test-retest reliability. Validity has been proven by correlating physical activity data with maximum oxygen uptake (Frey et al., 1999).

#### *Falls Efficacy Scale - International*

The German version of the Falls Efficacy Scale - International (FES-I) was used to measure falls self-efficacy (Dias et al., 2006). The participants had to report their level of concern about falling when performing different activities on a 4-point Likert-scale (1 = not at all concerned to 4 = very concerned). For statistical analyses, the summed score of all 16 items was used. The FES-I showed a high test-retest reliability and internal validity (Yardley et al., 2005).

#### *Digit Symbol Substitution Test*

The Digit Symbol Substitution Test (DSST) is a subtest from the Wechsler adult intelligence scale - III (Wechsler, 1997). It assesses neurocognitive functions such as attention, short-term memory and graphomotor skills (Bettcher, Libon, Kaplan, Swenson, & Penney, 2011). The participants were initially confronted with a table containing the numbers from 1 to 9. Under

each number was a corresponding geometric symbol. Subjects were then asked to transcribe the unique geometric symbols in a blank box under prescribed boxes with numbers. The number of correct items completed within 90 s was counted.

#### *World health organization quality of life - bref*

Health-related quality of life was assessed using the German version of the World health organization quality of life - bref questionnaire (QoL) (Angermeyer, Kilian, & Matschinger, 2000). The QoL refers to four outcome-domains (physical health, psychological health, social relationship and environment). In the present thesis, the physical health domain was used. Scores range from 0 to 100, with a higher score indicating a better quality of life. The QoL domain-scores revealed good test-retest reliability as well as discriminant and construct validity (Skevington, Lotfy, & O'Connell, 2004).

#### *4.2.11 Assessment of study quality*

To assess the methodological quality of the included studies of Publication IV, the Physiotherapy Evidence Database (PEDro) scale was used (Maher, Sherrington, Herbert, Moseley, & Elkins, 2003). The PEDro scale rates the internal validity and the presence of statistically replicable information of RCTs with scores ranging from 0 (low quality) to 10 (high quality). A score of  $\geq 6$  represents the cut-off value for high-quality studies (Maher et al., 2003).

### **4.3 Balance and resistance training protocol**

The effects of supervised versus unsupervised CRT on measures of balance and muscle strength/power in older adults were examined in a longitudinal study (Publication III). This paragraph contains a brief presentation of the basic principles of the applied training protocol. A detailed description of the protocol can be found in Publications II and III.

Participants of the two IGs (i.e., SUP and UNSUP) conducted a 12-week CRT program with three training sessions per week on non-consecutive days. Each session lasted 45 minutes. The exercise program was based on recommendations developed by an expert panel and is publicly accessible (<http://www.bfu.ch/de/fuer-fachpersonen/sturzpraevention/training-im-alter>). All exercises were performed using participants' own body weight or with the help of low-cost equipment (e.g., towels, bottles, balls). The intensity of the training was examined with the Borg scale (6-20 points) (Borg, 1982). Participants had to perform each exercise with a rate of perceived exertion of 12 to 16 ('somewhat hard' to 'hard').

Exercises comprised static balance exercises, dynamic balance exercises and strength/power exercises for leg and trunk muscles. Regarding static balance exercises (basic exercise: upright, bipedal stance) and dynamic balance exercises (basic exercise: normal gait), subjects performed 4 series of 20-60 s for each exercise with a rest of 30 s between the series. Training intensity of balance exercises was adjusted using predefined progressive exercise routines (e.g., reduction of base of support, additional motor/cognitive tasks, inclusion of unstable surfaces). In terms of muscle strength/power exercises (basic exercises: squats, plank, standing side leg lifts, calf raises/toe raises, standing trunk extensions), participants performed 3 series of 8-15 repetitions for each exercise with a rest of 60-120 s between series. Progressive exercise routines with different intensity stages were compiled from the given strength/power exercises using different strategies (e.g., from static to dynamic exercises, from slow to fast movement velocity, inclusion of unstable surfaces).

The SUP group exercised supervised twice a week at a local gym, and once a week unsupervised at home. The UNSUP group followed the same exercise routine as SUP, except that they trained unsupervised at home three times per week. Quantity and quality of the training were controlled by phone calls every fortnight and a training log book. The intervention period was followed by a 12-week detraining period for both IGs. Participants of the CG maintained their habitual physical activity level.

#### **4.4 Statistical analyses**

Data are presented as group mean values  $\pm$  standard deviations (SD) or medians and interquartile ranges. Regarding the cross-sectional study (Publication I), associations of strength and balance variables were examined using Pearson product-moment correlation coefficients. Associations are reported by their correlation coefficient, level of significance, and the amount of variance explained. Additionally, simple linear regression models were calculated to determine the most robust predictors of the respective outcome variables.

An a priori power analysis was conducted for Publication III in order to detect the sample size needed for medium-sized group  $\times$  time interaction effects. A multivariate analysis of variance (MANOVA) was computed to analyze baseline differences. Effects of training were analyzed in separate 3 (group: SUP, UNSUP, CG)  $\times$  3 (time: pre, post, follow-up) ANOVA with repeated measures on time. For non-parametric variables, Kruskal-Wallis one-way ANOVA and Friedman tests were used. Effect sizes (Cohen's *d*) were determined. Effect sizes help to assess whether a difference is of practical concern. Cohen's *d* values of 0.20 indicate small



effects, values of 0.50 indicate medium effects, and values of 0.80 indicate large effects (Cohen, 1992). As an estimate of effect sizes in non-parametric post hoc tests,  $PS_{dep}$  scores (probability of superiority for dependent samples) were computed (Grissom & Kim, 2012).

To examine the effects of supervised compared with unsupervised BT and/or RT (Publication IV), we calculated between-subject standardized mean differences according to the following formula:

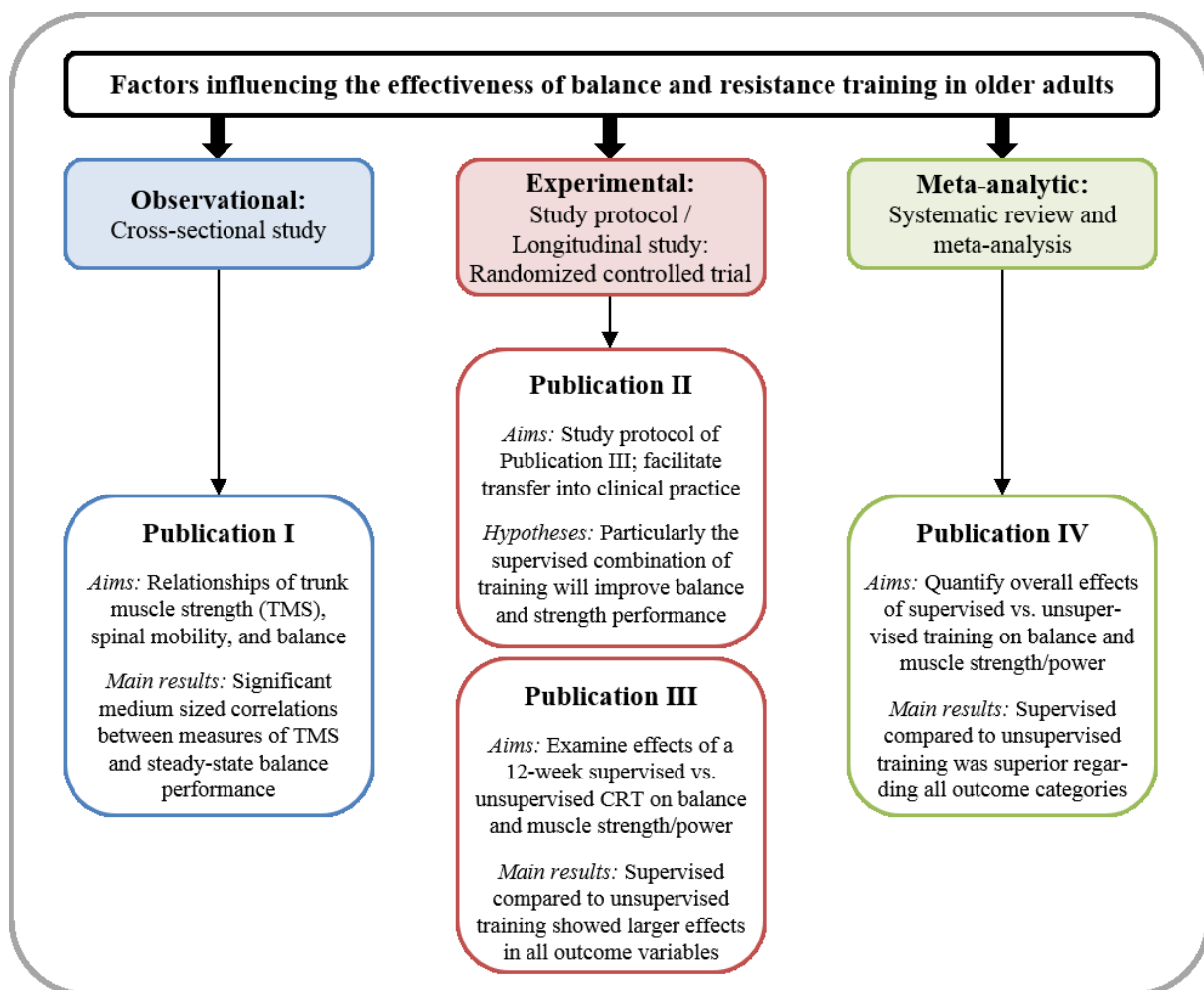
$$SMD_{bs} = [mean\ post\ value\ intervention\ group - mean\ post\ value\ control\ group] \div pooled\ standard\ deviation.$$

The  $SMD_{bs}$  was adjusted for sample size (Hedges & Olkin, 1985) and a random-effects meta-analysis model was applied to compute the weighted mean  $SMD_{bs}$  with 95 % confidence intervals for each pre-defined outcome category (i.e., static steady-state/dynamic steady-state/proactive/reactive balance, balance test batteries, dynamic muscle strength/power of lower extremities). Weighted mean  $SMD_{bs}$  allow a quantitative examination of the effects of SUP versus UNSUP. Additionally, they help to determine whether the detected differences are of practical concern (see the cut-offs mentioned in the last paragraph).

Statistical analyses were performed with the software Statistical Package for Social Sciences (SPSS) version 21.0 and 22.0 (IBM, Chicago, IL, USA) or Review Manager version 5.3 (The Cochrane Collaboration, Copenhagen, Denmark). The significance level was set at  $p < 0.05$ . Detailed information on all applied statistical analyses is provided in the respective publications.

## 5. Results

The following chapter summarizes the results of the studies included in this doctoral thesis which examined (a) the relationships of trunk muscle strength, spinal mobility, and balance in older adults; (b) the comprehensive effects of CRT on measures of balance and muscle strength/power; and (c) the effects of SUP versus UNSUP on measures of balance and muscle strength/power in older adults. Figure 5 provides an overview of the main findings. Detailed information can be found in the respective publications (Appendix, Publications I to IV).



**Figure 5:** Schematic overview of the aims and main results of this doctoral thesis (Publications I to IV). CRT = combined balance and resistance training; TMS = trunk muscle strength

## 5.1 Publication I: “Relationships between trunk muscle strength, spinal mobility, and balance performance in older adults”

*Aims and hypotheses:* The aim of Publication I was to investigate associations between measures of trunk muscle strength (i.e., maximal isometric strength in flexion, extension, lateral flexion, rotation)/spinal mobility (i.e., mobility in coronal and sagittal planes) and static/dynamic steady-state (i.e., tandem stance; 10-m walk test), proactive (i.e., TUG), and reactive (i.e., ML perturbation impulse) balance in older adults. It was hypothesized that both TMS and spinal mobility are related to measures of steady-state, proactive, and reactive balance.

*Results:* Thirty-four participants (male: 16, female: 18) with a mean age of  $70.4 \pm 4.4$  years were included in the study. Between all measures of TMS and static steady-state balance (i.e., summed CoP displacements during tandem stance) significant correlations were detected. The  $r$  values ranged from 0.43 to 0.57 (all  $p < 0.05$ ), indicating medium effect sizes. Additionally, significant positive correlations were observed between specific measures of TMS (i.e., maximal isometric strength in flexion, extension, and rotation) and dynamic steady-state balance (i.e., stride length). Significant  $r$  values ranged from 0.42 to 0.55 (all  $p < 0.05$ ). No significant correlations were found between TMS and specific measures of dynamic steady-state (i.e., stride time, stride velocity), proactive (TUG), and reactive balance (summed oscillations during step stance following a perturbation impulse;  $r \leq 0.28$ ; all  $p > 0.05$ ). Between all variables of spinal mobility and balance, no significant correlations were observed ( $r \leq 0.23$ ; all  $p > 0.05$ ). Simple linear regression analyses for the predictor variables of TMS and the criterion parameters balance revealed that TMS explains between 1-33 % of the total variance in the respective balance variables.

### **Publication I was published as follows:**

Granacher, U., Lacroix, A., Roettger, K., Gollhofer, A., & Muehlbauer, T. (2014). Relationships between trunk muscle strength, spinal mobility, and balance performance in older adults. *Journal of aging and physical activity*, 22(4), 490-498. doi: 10.1123/japa.2013-0108 (Granacher, Lacroix, Roettger, Gollhofer, & Muehlbauer, 2014)

The final publication is available at <http://journals.humankinetics.com/doi/abs/10.1123/japa.2013-0108>

## 5.2 Publication II: “A best practice fall prevention exercise program to improve balance, strength/power, and psychosocial health in older adults: study protocol for a randomized controlled trial”

*Aims:* Publication II is a study protocol for a randomized controlled trial (Publication III) investigating the effects of a 12-week supervised CRT program compared with a 12-week unsupervised CRT program on intrinsic fall risk factors and psychosocial health in older adults. The training protocol comprises static balance exercises, dynamic balance exercises and resistance exercises for leg and trunk muscles with three training sessions of 45 minutes per week. The study protocol was published in order to facilitate transfer of the expert-based practice guide into clinical practice. Practitioners, exercise therapists, and instructors will be provided with a feasible, validated exercise routine whose effect on intrinsic fall risk factors will be scientifically evaluated in Publication III of this thesis.

*Hypotheses:* It was hypothesized that the training protocol of the proposed trial would positively influence balance and muscle strength/power, as well as cognition, psychosocial well-being, and falls self-efficacy in community-dwelling people. Further, particularly the supervised combination of BT and RT was hypothesized to improve performance in the aforementioned measures.

*Transfer into clinical practice:* Four years after publication, the study protocol has been accessed more than 39,000 times on the journal’s webpage (<https://bmcgeriatr.biomedcentral.com/articles/10.1186/1471-2318-13-105>). Additionally, 29 articles cited the protocol between October 2013 and September 2017.

### **Publication II was published as follows:**

Gschwind, Y. J., Kressig, R. W., Lacroix, A., Muehlbauer, T., Pfenninger, B., & Granacher, U. (2013). A best practice fall prevention exercise program to improve balance, strength/power, and psychosocial health in older adults: study protocol for a randomized controlled trial. *BMC Geriatrics*, 13, 105. doi: 10.1186/1471-2318-13-105 (Gschwind et al., 2013)

The final publication is available at <https://bmcgeriatr.biomedcentral.com/articles/10.1186/1471-2318-13-105>

### 5.3 Publication III: “Effects of a supervised versus an unsupervised combined balance and strength training program on balance and muscle power in healthy older adults: a randomized controlled trial”

*Aims and hypotheses:* The aims of this study were to examine the effects of a 12-week CRT on measures of static/dynamic steady-state, proactive, and reactive balance, lower extremity muscle strength/power (primary outcomes), falls efficacy, cognitive function, quality of life, and body composition (secondary outcomes) in healthy older adults. We compared the effects of a supervised version of the training protocol published in Publication II (SUP) with an unsupervised version (UNSUP). Additionally, detraining effects were detected. It was hypothesized that the CRT would result in significant improvements in primary and secondary outcomes as compared to an inactive CG and that the supervised program (SUP) would elicit larger performance enhancements compared to the unsupervised program (UNSUP). Further, it was hypothesized that training-related improvements would remain above baseline values after 12 weeks of detraining in both the SUP and UNSUP.

*Results:* Sixty-six healthy, mobile older adults (male: 25, female: 41) with a mean age  $72.8 \pm 3.8$  years participated in the study. Adherence rates to training were high for both training groups (SUP: 92 %; UNSUP: 97 %). For all primary outcome categories (i.e., steady-state/proactive/reactive balance and muscle strength/power), significant group  $\times$  time interactions (all  $p < 0.05$ ) in favor of both training groups compared to the CG were found. Significant performance enhancements from pre to post (post hoc) in the training groups showed effects of  $0.62 \leq d \leq 1.82$  (6 % to 68 %) for measures of balance and  $0.71 \leq d \leq 2.86$  (12 % to 29 %) for measures of lower extremity muscle strength/power.

No significant group  $\times$  time interaction effects were found for dual-task walking falls efficacy, cognitive function, quality of life, and body composition, except for the variable lean tissue mass of the legs. Post hoc analyses revealed larger training-related effects for the SUP group ( $0.26 \leq d \leq 2.86$ ) compared to the UNSUP group ( $0.06 \leq d \leq 2.30$ ) in most of the assessed variables. More specifically, SUP showed larger effects from pre to post compared to UNSUP in the Romberg Test [ $d = 1.00$  (SUP) vs.  $0.33$  (UNSUP)], stride velocity ( $d = 0.62$  vs.  $0.24$ ), stride length ( $d = 0.26$  vs.  $0.06$ ), coefficient of variation of stride velocity ( $d = 0.73$  vs.  $-0.74$ ), coefficient of variation of stride length ( $d = 0.72$  vs.  $-0.33$ ), TUG ( $d = 0.85$  vs.  $0.44$ ), FRT ( $d = 1.82$  vs.  $0.65$ ), PRT (*Probability of superiority* =  $0.98$  vs.  $0.95$ ), CST ( $d = 1.61$  vs.  $0.84$ ), and SAT ( $d = 1.69$  vs.  $0.82$ ). Regarding the SDT ( $d = 1.76$  vs.  $1.75$ ), effect sizes of

SUP versus UNSUP were comparable. Following detraining, significantly enhanced performances compared to baseline were still present in 13 variables for the SUP group ( $0.33 \leq d \leq 2.82$ ) and in 10 variables for the UNSUP group ( $0.59 \leq d \leq 2.74$ ).

**Publication III was published as follows:**

Lacroix, A., Kressig, R. W., Muehlbauer, T., Gschwind, Y. J., Pfenninger, B., Bruegger, O., & Granacher, U. (2016). Effects of a supervised versus an unsupervised combined balance and strength training program on balance and muscle power in healthy older adults: a randomized controlled trial. *Gerontology*, 62(3), 275-288. doi: 10.1159/000442087 (Lacroix et al., 2016)

The final publication is available at <https://www.karger.com/Article/FullText/442087>

#### **5.4 Publication IV: “Effects of supervised versus unsupervised training programs on balance and muscle strength in older adults: a systematic review and meta-analysis”**

*Aims and hypotheses:* The aims of this systematic review and meta-analysis were to quantify the effects of supervised versus unsupervised BT and/or RT programs on measures of balance (static/dynamic steady-state balance, proactive balance, reactive balance, and balance test batteries) and measures of muscle strength/power (dynamic muscle strength and muscle power with isotonic muscle contractions) performance in healthy older adults. In addition, dose-response relationships of exercise supervision (i.e., number of additional supervised sessions in supervised training groups; presence or absence of supervised sessions in unsupervised training groups) were evaluated. Based on the findings of single RCTs and meta-analyses in clinical populations, we hypothesized that supervised BT and/or RT programs would be superior to unsupervised BT and/or RT programs in improving healthy older adults’ balance and muscle strength/power.

*Results:* After the screening process, 11 studies were included in the quantitative analysis (Almeida et al., 2013; Boshuizen, Stemmerik, Westhoff, & Hopman-Rock, 2005; Cyarto et al., 2008b, 2008a; Donat & Oezcan, 2007; Hinman, 2002; Karahan et al., 2015; Lacroix et al., 2016; Lindemann, Rupp, Muche, Nikolaus, & Becker, 2004; Opdenacker, Delecluse, & Boen, 2011; van Roie et al., 2010; Watson et al., 2015; Wu et al., 2010) with a total of 621 participants (male: 209, female: 412; mean age: 73.6 years, range group means: 65.3-81.1 years). Statistical analyses revealed that supervised BT and/or RT was superior compared with unsupervised BT and/or RT in improving measures of static steady-state balance (weighted mean  $SMD_{bs} = 0.28$ ,  $p = 0.39$ ), dynamic steady-state balance ( $SMD_{bs} = 0.35$ ,  $p = 0.02$ ), proactive balance ( $SMD_{bs} = 0.24$ ,  $p = 0.05$ ), balance test batteries ( $SMD_{bs} = 0.53$ ,  $p = 0.02$ ), and measures of muscle strength/power ( $SMD_{bs} = 0.51$ ,  $p = 0.04$ ). Regarding dose-response relationships, the analyses showed that a total of 10-29 additional supervised sessions in the supervised training groups as opposed to the unsupervised training groups resulted in the largest effects for static steady-state balance (weighted mean  $SMD_{bs} = 0.35$ ), dynamic steady-state balance ( $SMD_{bs} = 0.37$ ), and muscle strength/power ( $SMD_{bs} = 1.12$ ). Thirty or more additional supervised sessions in the supervised training groups produced the largest effects on proactive balance (weighted mean  $SMD_{bs} = 0.30$ ) and balance test batteries ( $SMD_{bs} = 0.77$ ). Larger effects in favor of SUP were found when compared to studies that did not include any super-

vised sessions in their UNSUP (weighted mean  $SMD_{bs}$ : 0.28 to 1.24). When compared with studies that implemented a few supervised sessions in their UNSUP (e.g., three supervised sessions throughout the entire intervention program), effects in favor of the SUP were smaller ( $SMD_{bs}$ : -0.06 to 0.41).

**Publication IV was published as follows:**

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The final publication is available at <https://link.springer.com/article/10.1007/s40279-017-0747-6>



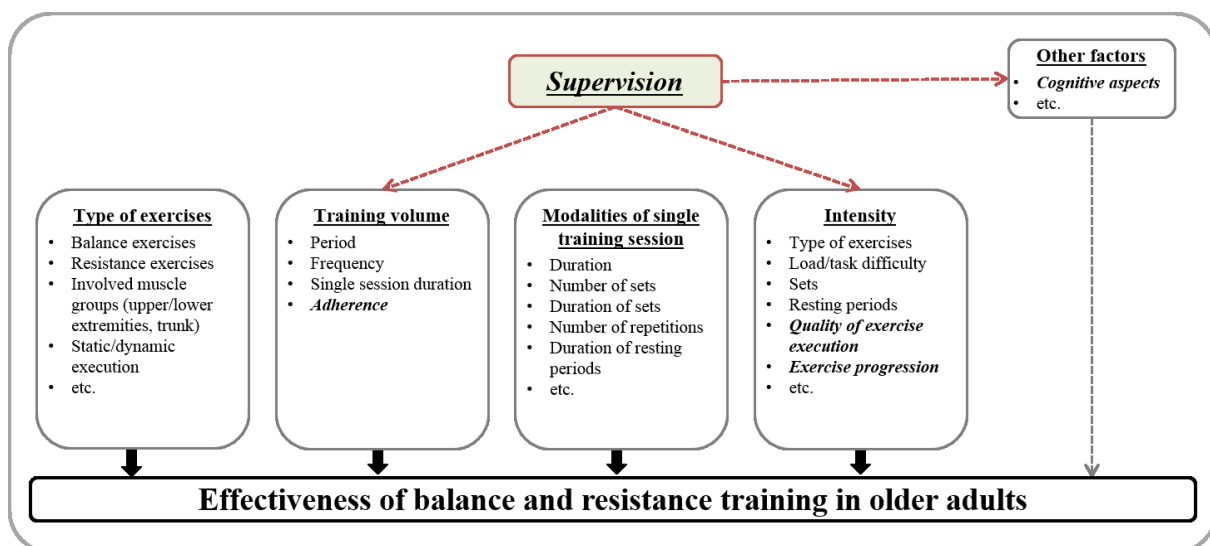
## **6. General discussion**

In this doctoral thesis, a cross-sectional study (Publication I), a study protocol for a RCT (Publication II), a longitudinal study (Publication III), and a systematic review and meta-analysis (Publication IV) were incorporated to complement the existing knowledge of factors influencing the effects of BT and RT in older adults. In a comprehensive methodological approach using a wide range of performance measures, the relationship between trunk muscle strength and balance performance, the comprehensive effects of CRT, as well as the role of supervision in BT and RT interventions in older adults were evaluated. The findings of this thesis revealed that measures of trunk muscle strength and static/dynamic steady-state balance are correlated statistically significant and that CRT seems to be an effective exercise intervention to improve a wide range of balance and muscle strength/power measures in older adults. Additionally, both our longitudinal study and meta-analysis showed that supervised BT and/or RT improves balance and muscle strength/power of older adults to a larger extent than comparable unsupervised interventions. The following chapters discuss the main results of the included publications by integrating the findings into the already existing body of knowledge.

### **6.1 Factors influencing the effectiveness of balance and resistance training in older adults**

Previous studies demonstrated that BT and/or RT have the potential to improve intrinsic fall risk factors in the elderly, depending on the applied training protocol (see Chapter 2.3). Considering future challenges arising from population aging from a societal perspective (see Chapter 1.1) and biological aging from an individual perspective (see Chapter 2.1), there is the need for a widespread implementation of exercise programs that most effectively enhance balance and muscle strength/power in older adults. Factors influencing the effectiveness of BT and/or RT in the elderly population are manifold and have been described in the literature, comprising various exercise and training modalities such as type of exercises, involved muscle groups, static/dynamic exercises, volume, total number of training sessions, training period, frequency of sessions per week, duration of training per week, duration of a single training session, number of sets, duration of sets, number of repetitions (RT), time under tension (RT), duration of resting periods between sets, exercise progression (i.e., regulative modalities to encounter adaptations to training like progressive exercise routines), and exercise intensity (i.e., exertion during an exercise relative to the limits of an individual's capacity).

How can the findings of this doctoral thesis complement existing practical recommendations of BT/RT in the elderly? In general, the results of the present thesis support the hypotheses that the implementation of balance, trunk muscle resistance, and lower extremity resistance exercises (Publications I and III) as well as the supervision of the exercise (Publications III and IV) may be beneficial in order to enhance balance and muscle strength/power performance in older adults. Thus, conclusions of the current thesis complement already identified important modalities of BT/RT in terms of ‘type of exercises’ (i.e., inclusion of balance, trunk/lower extremity resistance exercises) and ‘supervision’ (i.e., supervision should be applied, if possible). Beneficial effects of supervision may be attributed to an enhanced exercise adherence (i.e., enhancing training volume), a higher quality in the execution of the exercises and a more suitable individually tailored exercise progression (i.e., enhancing training intensity), or unknown influences on cognitive aspects (e.g., executive function) (Figure 6). The following chapters (6.2, 6.3, and 6.4) will discuss the main findings of this thesis in detail.



**Figure 6:** Schematic figure illustrating potential reasons of how exercise supervision increases the effectiveness of balance and resistance training in older adults. Potentially influenced factors are highlighted in italic and bold. Additional potential associations between the different exercise modalities are not shown.

## 6.2 Potential benefits of enhanced trunk muscle performance in older adults

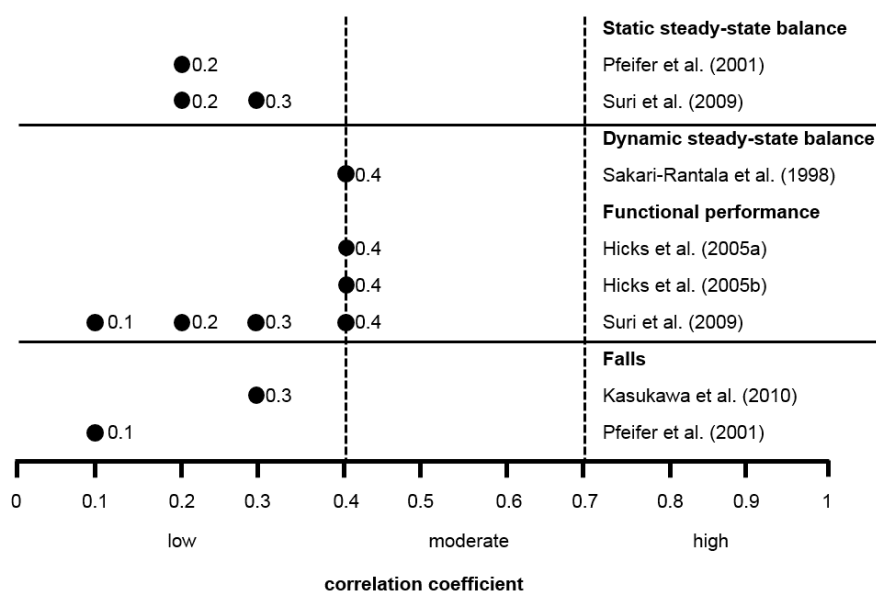
Findings of this doctoral thesis indicate that the inclusion of trunk muscle exercises in BT/RT programs for older adults may be beneficial, as measures of TMS and static/dynamic steady-state balance were correlated statistically significant (Publication I) and a CRT involving trunk muscle exercises (supervised and unsupervised) significantly improved balance and muscle strength/power performance in older adults compared to a CG (Publication III). How-

ever, direct transfer effects of the implemented trunk muscle exercises in Publication III cannot be elucidated because of the interfering effects of other involved exercises (i.e., balance and lower extremity resistance exercises). The fact that only 2 of the 11 included studies of Publication IV implemented trunk muscle exercises indicates that there is a need for further longitudinal studies examining the transferability of enhanced TMS on balance performance in the elderly.

In terms of associations between TMS/spinal mobility and balance performance in old age, the main results of this thesis are: (1) all measures of TMS are correlated statistically significant with static steady-state balance ( $r$  values ranging from 0.43 to 0.57); (2) specific measures of TMS were correlated statistically significant with dynamic steady-state balance ( $r$  values ranging from 0.42 to 0.55); (3) all measures of TMS and reactive as well as proactive balance were not associated statistically significant (Publication I). Further, (4) analyses revealed no statistically significant correlations between all variables of spinal mobility and balance performance (i.e., steady-state, proactive, and reactive) (Publication I). Thus, *Hypothesis 1* can only partially be supported.

Regarding the associations between measures of TMS and balance, our results revealed statistically significant correlations with  $r$  values ranging between 0.42 and 0.57. The observed correlations are in accordance with the literature and only slightly above the small- to medium-sized associations between variables of TMS, balance, and falls reported in previous studies (see Figure 7). However, the findings of this thesis exceed those reported in the literature, because previous studies involved ill/frail subjects (Pfeifer et al., 2001; Suri et al., 2009), assessed TMS only in specific movement directions (Pfeifer et al., 2001; Sakari-Rantala, Era, Rantanen, & Heikkinen, 1998; Suri et al., 2009), assessed TMS indirectly via trunk muscle mass/cross-sectional area (Hicks et al., 2005a, 2005b), or assessed only specific categories of balance performance (Pfeifer et al., 2001; Sakari-Rantala et al., 1998). Publication I of this doctoral thesis is the first study that examined associations between measures of TMS/spinal mobility and balance (i.e., static/dynamic steady-state, proactive, reactive) in healthy older adults using a methodologically comprehensive approach.

Our results showed significant relationships between various measures of TMS and static/dynamic steady-state balance. More detailed, trunk muscle strength in flexion, extension, and rotation seem to be associated with static steady-state balance and specific measures of dynamic steady-state balance, but not with measures of proactive and reactive balance.



**Figure 7:** Relationship between trunk muscle strength/composition and static steady-state balance, dynamic steady-state balance, and falls in older adults as reported in the literature. Figure published in Publication I (Granacher, Lacroix et al., 2014); doi: 10.1123/japa.2013-0108

Based on these findings it can be hypothesized that exercise programs aiming at enhancing static and dynamic steady-state balance in older adults should include exercises for the trunk muscle flexors, extensors, and rotators. Further, results indicate that such TMS exercises should be performed with a high level of intensity, because significant associations were found between measures of maximal TMS and balance. Due to the fact that cross-sectional analyses do not allow for conclusions on cause-and-effect relationships, the functional interpretation of these findings has to be treated with caution. Yet, the findings of this thesis (i.e., non-significant correlations between measures of TMS and both reactive and proactive balance) and of other cross-sectional studies (e.g., Muehlbauer, Besemer et al., 2012; Muehlbauer, Gollhofer, & Granacher, 2012) suggest that proactive and reactive balance are independent of other conditions and should be tested and trained complementarily in future fall-preventive CRT interventions. To verify our findings, longitudinal studies are needed that examine the effects of trunk muscle RT on balance performance. In this context, Granacher et al. (2013) reported in their systematic review that trunk muscle RT seems to have positive effects on balance performance in older adults. Furthermore, such exercise programs seem to be feasible and safe. Following nine weeks of trunk instability RT, Granacher et al. (2014) reported an attendance rate of 92 % in the IG and no training-related injuries.

What are possible reasons for the associations between measures of TMS and steady-state balance? In Chapter 2.3.3 it was highlighted that the trunk can be seen as the mechanical linkage between the upper and lower extremities. Thus, one may argue that those older adults with high levels of TMS have a larger trunk stability and may therefore coordinate their upper and lower extremities more effectively during static (i.e., standing) and dynamic (i.e., walking) balance tasks. A large number of synergetic and antagonistic muscles are involved in the stabilization of the trunk by muscular coactivation, including global (e.g., rectus abdominis, erector spinae, external obliques) and local muscles (e.g., transverse abdominis, lumbar multifidus) (Cresswell, Oddsson, & Thorstensson, 1994; Henry, Fung, & Horak, 1998). The primary function of global muscles is the production of torque and transfer of load between the thorax and the pelvis. Local muscles stabilize the lumbar spine during whole body movements and postural adjustments (Bergmark, 1989). The results of Publication I of this thesis revealed significant associations between maximal isometric TMS and specific variables of steady-state balance, indicating that, apart from their primary role in torque production and load transfers, global muscles might additionally contribute to the mechanical stability of the trunk. It has been argued in the literature that global muscles may indirectly influence trunk stability by controlling loads produced through limb movements, so that the resulting force transferred to the lumbar spine is attenuated (Bergmark, 1989). In fact, Hodges and Richardson (1997) showed that global muscles (e.g., rectus abdominis, obliqui) contract in anticipation of lower limb flexion and extension movements to stabilize the lumbar spine. This feedforward mechanism has been identified for other global muscles in advance of upper limb movements (Aruin & Latash, 1995). Owing to these findings it seems reasonable to argue that during external perturbations (e.g., upper/lower limb movements), anticipatory trunk muscle contractions are necessary to maintain postural stability (Hodges & Richardson, 1999). These mechanisms (i.e., less spinal movements through better coordination of limbs and beneficial anticipatory adjustments) of enhanced TMS may also have contributed to the enhanced balance performance after CRT in Publication III. However, this assumption cannot finally be clarified, since other exercise components were involved in the training (see Chapter 6.3). Likewise, the influence of trunk muscle exercises on the effects found in Publication IV remains unclear (see Chapter 6.4). In summary, the findings of Publication I of this thesis contribute to the hypothesis that adequate TMS performance appears to be necessary for maintaining balance during standing (i.e., static steady-state balance) and walking (i.e., dynamic steady-state balance).

The initial hypothesis of this thesis (*Hypothesis 1*) that measures of spinal mobility and balance are associated cannot be supported by our results. It has been shown in previous studies that spinal mobility (i.e., cervical and lumbar) decreases with age (Haemaelaenen et al., 2006; Schenkman, Shipp, Chandler, Studenski, & Kuchibhatla, 1996) and is associated with improved trunk muscle strength (Balogun et al., 1992). Due to the fact that trunk muscle composition also predicts balance performance in the elderly (Hicks et al., 2005b; Suri et al., 2009), it was hypothesized in Publication I that spinal mobility and balance performance should be significantly associated. This hypothesis was reinforced by findings from Kasukawa et al. (2010), who showed that TMS, spinal deformity (i.e., lumbar kyphosis), and spinal mobility were significantly associated with the occurrence of falls in elderly subjects aged 60-92 years. However, our analyses cannot confirm this hypothesis, as only small and non-significant correlations between measures of spinal mobility (i.e., sagittal and coronal plane) and balance (i.e., static/dynamic steady-state, proactive, and reactive) were detected in healthy physically active older adults. It appears that other factors also moderate the associations between spinal mobility and balance. One possible moderating factor may be the age of participants. For example, Miyakoshi et al. (2005) showed that spinal mobility was significantly associated with age ( $r = -0.412$ ) and lumbar kyphosis angle ( $r = -0.284$ ) in elderly subjects with a mean age of 70.2 years. Further, it has been discussed that decreased spinal mobility might be a predictor of hyperkyphosis, which is in turn moderated by TMS (Mika, Fernhall, & Mika, 2009; Miyakoshi et al., 2005).

Another factor possibly influencing the association between spinal mobility and balance is the physical mobility status of older adults. Notably, acute spinal mobility was significantly lower in older adults (mean age 74.2) with a history of falls compared to a group of elderly individuals without a history of falls (Kasukawa et al., 2010). Kasukawa et al. (2010) also utilized logistic regression analysis and found that the presence/absence of falls was significantly associated with measures of back extensor strength (coefficient =  $-0.342$ ), lumbar kyphosis (coefficient =  $0.075$ ), spinal inclination (coefficient =  $0.073$ ), and mobility of the lumbar spine (coefficient =  $-0.058$ ) in the elderly. Considering associations between spinal mobility and hyperkyphosis, falls, as well as quality of life (Imagama et al., 2011; Miyakoshi et al., 2007), especially mobility-limited older adults could benefit from the assessment and training of spinal mobility. These assumptions, however, need further verification. Based on the findings of Publication I, spinal mobility and balance performance are not associated in healthy, community-dwelling older adults with high levels of physical activity.

Nevertheless, it has been shown in this thesis that TMS and various measures of steady-state balance are associated in this population. These findings are in accordance with the literature and it has been hypothesized that TMS-promoting exercises should be included in fall-preventive exercise programs for healthy older adults. This hypothesis has been reinforced by the findings of a systematic review that examined the effects of core strength training programs on TMS, balance, and functional performance in older adults (Granacher et al., 2013). The authors concluded that core strength training has the potential to improve measures of TMS, balance, and functional performance in seniors with mean effect sizes ranging from 0.88 to 0.99. Given the low methodological quality of the included studies, the authors stated that there is a need for more high-quality studies to validate the transferability of TMS on balance performance in healthy older adults. The findings of Publication I and initial promising longitudinal studies have led to the inclusion of TMS-promoting exercises in the training protocol of Publications II and III of this thesis. In order to mitigate as many intrinsic fall risk factors as possible, exercises promoting all aspects of balance (i.e., static/dynamic steady-state, proactive, and reactive balance) as well as lower extremity muscle strength/power (i.e., exercises targeting gluteal, quadriceps, ischiocrural, gastrocnemius/soleus/tibialis muscles; to a lower extent upper back muscles trapezius and deltoid) were additionally involved in the training protocol. The following Chapter 6.3 will discuss the effects of this CRT program.

### **6.3 Effects of combined balance and resistance training in older adults**

The results of this thesis indicate that CRT is a safe, feasible and effective means to improve important intrinsic fall risk factors in older adults (Publication III). In fact, no training-related injuries were observed during the 12-week CRT of Publication III. The CRT studies included in the meta-analysis of Publication IV (6 out of 11 eleven studies) also reported no adverse events following training. The low dropout rate (i.e., 9.1 %) and high attendance rates (i.e., mean attendance 94.5 %) during the CRT of Publication III as well as the moderate dropout rates in the CRT groups of Publication IV (i.e., mean dropout rate 20.2 %) indicate that CRT is a practicable exercise intervention in healthy older adults.

The following paragraphs will discuss the main findings of this thesis regarding the effects of CRT in detail. Publication II will not be discussed in a separate paragraph, because it represents a study protocol for a RCT that was applied in Publication III. Nevertheless, Publication II fulfilled its purpose of facilitating transfer of the expert-based practice guide into clinical practice. Until September 2017, the article was accessed more than 39,000 times on the jour-

nal's webpage (<https://bmcgeriatr.biomedcentral.com/articles/10.1186/1471-2318-13-105>) and also cited by 29 articles. To ensure transparency, deviations from the originally intended study protocol will be discussed and explained in the limitations section of this thesis (Chapter 6.5).

In terms of the effects of CRT in the elderly, the main results of this thesis are: (1) 12 weeks of CRT resulted in significant improvements in important intrinsic fall risk factors [i.e., primary outcomes: static steady-state balance (ROM), dynamic steady-state balance (10 m walking test: stride velocity, coefficients of variation), proactive balance (TUG, FRT), reactive balance (PRT) and lower extremity muscle power (CST, SAT, SDT)]; (2) most balance and muscle power variables remained above baseline values following 12 weeks of CRT and 12 weeks of detraining (Publication III). Thus, the results of Publication III confirm *Hypotheses 2 and 4* of this doctoral thesis.

Significant group  $\times$  time interaction effects in favor of the CRT groups were observed for all primary outcome parameters in Publication III of this thesis. Post hoc tests revealed significant performance enhancements from pre to post of  $0.62 \leq d \leq 1.82$  (6 % to 68 %) for balance outcomes and  $0.71 \leq d \leq 2.86$  (12 % to 29 %) for lower extremity muscle power outcomes. These improvements following a CRT intervention are in accordance with those reported in the literature. In this regard, Park et al. (2008) examined the effects of 48 weeks of CRT, conducted three times per week with elderly subjects aged 65 to 70 years. After the intervention period, the CRT group showed significant enhancements compared to an inactive CG in terms of static steady-state balance (i.e., CoF displacements, post hoc test:  $d = 2.03$ ; single leg stance standing time, post hoc test:  $d = 1.06$ ) and dynamic steady-state balance (i.e., 10 m fast walking time, post hoc test:  $d = 1.35$ ). In line with our findings for habitual stride length (Publication III), Park et al. (2008) found no significant differences for maximal step length. In a comparable study, Suzuki et al. (2004) evaluated the effects of a CRT program (three times weekly) on balance performance in elderly adults aged 73 and older. After 6 months of training, the IG significantly improved dynamic steady-state balance (i.e., steps in tandem gait,  $d = 0.54$ ) and proactive balance (i.e., FRT,  $d = 1.01$ ), while the CG did not. Consistent with our approach in Publication III, Zhuang et al. (2014) conducted a 12-week CRT (three times weekly) in older adults aged 60-80 years and assessed the effects on balance and lower extremity muscle strength. In this study, the IG significantly improved performance compared to an inactive CG regarding dynamic steady-state balance (i.e., spatiotemporal gait parameters, post hoc test:  $d = 0.59-1.06$ ), proactive balance (i.e., TUG, post hoc test:  $d = 0.73$ ), and lower



extremity muscle strength (i.e., isometric strength of knee flexor/knee extensor/ankle dorsiflexor/plantar flexor, post hoc test:  $d = 0.80-1.12$ ; 30s CST, post hoc test:  $d = 2.05$ ). Additionally, Gianoudis et al. (2014) observed the effects of a 6-month multimodal exercise program (three times weekly) including balance and strength exercises on lower extremity muscle strength/power in elderly subjects (mean age  $67 \pm 6$  years) compared to a CG. Significant improvements in favor of the IG were found for muscle strength/power (i.e., 30s CST, gain for IG: 11 %, gain in the CST in Publication III: 19 %; Timed Stair Climb, IG: 5 %, Publication III: 14 %).

Furthermore, the CRT studies included in Publication IV confirm the effects of CRT on balance and muscle strength/power found in Publication III. The mean improvement of balance performance (i.e., static/dynamic steady-state and proactive balance) across the CRT studies of Publication IV was 27.2 % and the mean improvement of lower extremity muscle strength/power (i.e., clinical tests measuring dynamic muscle strength/power) was 17.8%. Although it was not the goal to observe the effects of CRT in the meta-analysis of Publication IV of this thesis, the mean improvements of balance and muscle strength/power performance in the 6 CRT studies indicate that the results of Publication III are in accordance with the literature and are therefore relevant to the healthy older population.

What are potential adaptive processes following CRT in older adults? In the Chapters 2.3.1 and 2.3.2, underlying physiological mechanisms leading to functional improvements after BT/RT have been emphasized. The influence of various processes in the central nervous (i.e., affecting spinal and cortical levels) and neuromuscular system (i.e., affecting muscle fibers and activation patterns of muscles) following BT/RT has been highlighted in the literature, which may have contributed to the effects found in Publications III and IV. Due to our experimental approach, the underlying physiological mechanisms responsible for performance enhancements could not clearly be revealed. However, neural adaptations like an increased activation of prime movers, an improved coactivation of synergists, or a reduced coactivation of antagonists appear to be potential reasons for significant improvements of lower extremity muscle power, since the lean tissue mass of the legs and total skeletal muscle mass, as measured with bioelectrical impedance analysis, did not significantly increase after the CRT of Publication III (Aagaard et al., 2010; Haekkinen, 2003). Furthermore, the potential impact of enhanced TMS on balance performance cannot be solved, because we did not assess TMS in Publication III. The interference of other exercises (i.e., balance and lower extremity resistance) would also bias conclusions regarding the effects of trunk exercises. Likewise, the

two studies of Publication IV (meta-analysis) that included trunk muscle exercises cannot contribute to the explanation of such transfer effects. In a previous systematic review examining the effects of trunk/core RT on measures of TMS and balance in older adults, Granacher et al. (2013) concluded that such programs have the potential to improve balance (i.e., mean balance gain 23 %, mean effect size 0.88) and trunk muscle strength (mean strength gain 30 %, mean effect size 0.99). However, since the overall methodological quality of the included studies was rather weak and no meta-analysis was conducted, there is a need for more high-quality studies examining the effects of trunk/core RT on balance performance in older adults. Despite the positive effects on most of the primary outcome categories, the CRT program used in Publication III did not significantly improve gait performance under dual-task conditions. One possible explanation for the absent effects could be that we did not implement a sufficient number of exercises under dual-task conditions. In fact, exercise interventions that specifically aim at improving balance under dual-task conditions seem to have positive effects (Silsupadol et al., 2009). In terms of secondary outcomes, no significant group  $\times$  time interaction effects were found for body composition (i.e., main variables: body water, skeletal muscle mass), falls efficacy (i.e., FES-I), cognitive function (i.e., DSST), and quality of life (i.e., QoL). However, a tendency towards an improvement of quality of life was found within the supervised CRT group (i.e., improvement from pre to post 5 %). This may imply that the intervention period was too short to detect significant effects regarding the applied questionnaires.

Regarding detraining effects following CRT, the results of this thesis indicate that training-related improvements of balance and muscle strength/power are relatively stable, despite a longer period of training cessation. Most of the investigated variables of Publication III remained above baseline values following a 12-week detraining period after a CRT. Only a few studies are available that investigated detraining effects after CRT on balance performance in older adults. Seco et al. (2013) conducted a 9-month CRT followed by a 3-month detraining period. Participants in the IG (65-74 years) were able to maintain achieved levels of static steady-state balance (i.e., postural sway) from pre to follow-up, whereas participants older than 75 years were not able to stabilize baseline levels. Therefore, age may be an important moderating factor of detraining effects after a CRT in older adults. In terms of muscle strength/power, several previous RCTs examined detraining effects of CRT in the elderly (Carvalho et al., 2009; Helbostad et al., 2004a; Seco et al., 2013). In line with the findings of this thesis, Carvalho et al. (2009) found that performance improvements of 30s CST following

an 8-month multicomponent training in older women aged 64-85 years remained significantly above baseline value compared to a CG after 12 weeks of detraining. However, Seco et al. (2013) and Helbostad et al. (2004a) reported contrary findings. No relevant information on detraining effects is available from Publication IV of this thesis, as none of the included CRT studies (i.e., 5 out of 11 studies, excluding Publication III) examined effects of longer periods of training cessation. In summary, the findings regarding detraining effects in elderly subjects are heterogeneous and need further verification.

#### **6.4 Effects of supervision in balance and resistance training in older adults**

Concerning the effects of exercise supervision, the findings of this doctoral thesis indicate that supervised BT and/or RT programs are superior compared to unsupervised BT and/or RT programs in enhancing older adults' balance and muscle strength/power performance. Both a RCT conducting a 12-week CRT (Publication III) and a meta-analysis examining the effects of BT and/or RT programs (Publication IV) revealed more pronounced effects in supervised training groups compared to unsupervised training groups in various measures of balance and strength/power performance in healthy seniors. The main results of this doctoral thesis regarding the effects of exercise supervision are as follows: (1) a 12-week supervised CRT resulted in larger effects in most of the investigated variables (i.e., static/dynamic steady-state, proactive and reactive balance as well as muscle strength/power) compared to an unsupervised CRT (Publication III); (2) supervised compared to unsupervised BT and/or RT interventions showed larger effects in improving measures of balance and muscle strength/power ( $0.24 \leq \text{SMD}_{\text{bs}} \leq 0.53$ ; Publication IV); (3) an increasing number of supervised sessions in supervised compared to unsupervised BT and/or RT in elderly subjects revealed inconsistent dose-response relationships (i.e., a lower number of supervised sessions revealed larger effects for some outcome measures; Publication IV); (4) when compared with a specific form of unsupervised BT and/or RT including small doses of supervised sessions, the effects in favor of supervised BT/RT interventions were dampened (Publication IV). Thus, the findings of this doctoral thesis regarding the effects of supervision are consistent and confirm **Hypotheses 3** and **5**, while **Hypothesis 6** (i.e., dose-response relationships of supervision) can only partially be supported.

Both Publications III and IV found significant effects in favor of supervised regimens on all investigated outcome categories. More precisely, the observed effects sizes (i.e.,  $\text{SMD}_{\text{bs}}$ ) of Publication III are in accordance with the effects sizes found in Publication IV regarding dy-

dynamic steady-state balance (i.e.,  $SMD_{bs}$  Publication III 0.35 vs. weighted mean  $SMD_{bs}$  Publication IV 0.35) and overall balance performance (i.e., 0.35 vs. 0.40). In terms of static-steady state balance (i.e., 1.77 vs. 0.28), proactive balance (i.e., 0.61 vs. 0.24), and muscle strength/power (i.e., 1.12 vs. 0.51), effects sizes were larger in Publication III. These differences may most likely be explained by the different study designs. When comparing effects of studies that implemented completely unsupervised training groups (as done in Publication III), effect sizes of Publication III come closer to the weighted mean effect sizes found in Publication IV. In fact, regarding those studies, effects sizes for measures of static steady-state balance (i.e., Publication III 1.77 vs. Publication IV 1.00), proactive balance (0.61 vs. 0.28), and muscle strength/power (1.12 vs. 1.24) are more consistent. In the following paragraphs, the findings of Publications III and IV regarding effects and dose-response relationships of supervision will be discussed in detail, considering the already existing body of knowledge.

The results of Publication III of this thesis are partly in accordance with previous longitudinal studies examining the effects of supervision of a CRT in older adults. The SUP group of Publication III showed larger improvements compared to the UNSUP group for most of the investigated balance and strength/power variables (confirming *Hypothesis 3*). Most of the previous studies reported heterogeneous results, showing a superiority of SUP for specific measures (i.e., static steady-state balance, proactive balance, isometric muscle strength) but not for other assessed outcome variables (Cyarto et al., 2008b, 2008a; Donat & Oezcan, 2007; van Roie et al., 2010; Wu et al., 2010). Another study found that minimally supervised and fully supervised CRT programs may be equally effective in improving functional mobility (Almeida et al., 2013).

In this regard, Almeida et al. (2013) conducted a 4-month CRT (three sessions per week) and compared a fully supervised with a minimally supervised (i.e., once supervised every other week) form of the program in older adults (mean age  $78.6 \pm 4.5$  years). After the intervention period, change of dynamic steady-state balance (i.e., Tandem Walk test), proactive balance (i.e., TUG), balance test battery performance (i.e., Berg Balance Scale score) and lower extremity muscle power (i.e., Sit to Stand test) did not statistically differ between the fully and minimally supervised group. An explanation for absent effects of supervision may be that the minimally supervised group received additional supervised sessions. In another study, Donat and Oezcan (2007) showed that after 8 weeks of CRT (three times per week) measures of balance, position sense of the knee joint, and isometric lower extremity muscle strength improved for both a SUP and an UNSUP group in elderly persons aged 65 years and older. The

training resulted in significant improvements of static steady-state balance (i.e., single leg stance time, tandem stance time), proactive balance (i.e., time during TUG), balance test battery performance (i.e., Berg Balance Scale scores), and spinal mobility (i.e., angle in cm) for both groups. Isometric muscle strength (kg) and knee position sense (degree), however, only improved in the SUP group (all  $p < 0.05$ ). Because no inactive CG was involved and no group  $\times$  time interaction effects were computed, findings of this study have to be interpreted with caution. In contrast, the UNSUP group of Publication III of this thesis mainly improved proxies of lower extremity muscle power. This may be most likely explained by a high perceived training intensity (Borg scale 12-16), which has evoked large enhancements in previous studies (Fiatarone et al., 1990).

In line with the findings of Donat and Oezcan (2007), the studies of Cyarto et al. (2008b, 2008a) and Wu et al. (2010) observed a superiority of SUP for specific outcome variables. Cyarto et al. (2008b) reported significantly enhanced static steady-state balance (i.e., single leg stance time) in a SUP group compared to an UNSUP group (interaction effect:  $p = 0.05$ ) following 20 weeks (twice weekly) of CRT in elderly subjects aged 65-96. Although tendencies were observed in favor of the SUP group, performance change in other measures of balance (e.g., TUG) did not significantly differ between the groups. A possible reason for these heterogeneous findings might be that the UNSUP group in the study of Cyarto and colleagues (2008b) received nine home visits by an exercise instructor, which could have biased their results. Wu et al. (2010) observed the effects of 15 weeks (three times per week) of supervised versus unsupervised tai chi and strength exercises on balance performance in elderly subjects (mean age  $75.0 \pm 6.6$  years). Statistical analyses did not reveal significant group  $\times$  time interaction effects for proactive balance (i.e., TUG), but for static steady-state balance (i.e., body sway in quiet stance with eyes open) in favor of the SUP group (post hoc test SUP group:  $d = 0.48$ ). However, results were heterogeneous, as other measures of static steady-state balance (i.e., single leg stance time) did not change significantly in favor of SUP. Finally, van Roie et al. (2010) reported that 44 weeks of supervised versus unsupervised CRT caused significantly different performance changes in favor of the SUP group for machine-based tests (i.e., isometric/isokinetic strength tests), but not for clinical tests of lower extremity muscle strength/power (i.e., 30s CST, vertical jump). In Publication III, effects sizes were larger in SUP for every measure of lower extremity muscle strength/power. This discrepancy may be explained by additional supervised sessions in the UNSUP of van Roie et al. (2010) or by the high perceived intensity of the SUP of Publication III. In summary, previous studies on

the effects of supervision of CRT in seniors found heterogeneous results with tendencies indicating that supervised CRT may be more effective compared to unsupervised CRT.

However, effects in favor of SUP were even more pronounced in Publication III of this thesis. A conceivable reason for these differences may be the fact that the UNSUP of Publication III received no supervised sessions, whereas most of the CRT studies in the literature implemented additional supervised sessions in their UNSUP. This is in line with the findings of Publication IV on dose-response relationships of exercise supervision, indicating that the superiority of SUP is more pronounced when compared to fully unsupervised groups. Further, the profound exercise supervision by a professional instructor may have led to a higher quality in the execution of exercises in the SUP group of Publication III. Actually, the analysis of participants' exercise diaries revealed comparable mean stages of progression between SUP and UNSUP. This implies that exercises were performed more effectively and at a higher rate of exertion in SUP, causing larger adaptations. Additionally, the UNSUP group of Publication III mainly improved in muscle strength/power variables, not in balance. Particularly the participants' independent selection of an appropriate line of progression during BT may have negatively influenced balance outcomes of the UNSUP group. In terms of perceived intensity, RT is easier to control, since the applied Borg scale was originally developed to detect perceived exertion rather than a perceived difficulty level during BT. In this regard, participants of the UNSUP group may have exercised below an effective threshold to elucidate adaptations regarding all aspects of balance performance. If the goal is to improve all dimensions of balance-related fall risk factors with UNSUP, a higher dose may need to be applied, because a high level of perceived intensity cannot be ensured due to its uncontrolled nature. Due to the fact that participants of the UNSUP showed higher attendance, adherence rates are an unlikely reason for the superiority of SUP in Publication III. Cognitive function may also moderate the effects of supervision, although executive function (i.e., DSST score) did not significantly change between the groups of Publication III. A detailed discussion of possible reasons for the benefits of exercise supervision can be found on pages 59-62.

The previous paragraphs addressed the impact of exercise supervision in CRT programs (*Hypothesis 3*). The findings of our systematic review and meta-analysis (Publication IV) have shown that the effects of supervision are transferable to a broader range of exercise interventions, including BT, RT, and CRT. In this regard, supervised BT and/or RT programs showed larger effects compared to unsupervised programs in improving measures of balance and muscle strength/power in healthy seniors (Publication IV; confirming *Hypothesis 5*). The re-

sults of Publication IV complement recommendations from existing meta-analytic approaches for BT and RT in older adults (Borde et al., 2015; Lesinski et al., 2015b; Nicola & Catherine, 2011; Steib, Schoene, & Pfeifer, 2010). Regarding the investigated population, our data is relevant to healthy and mobile older adults. The results of Publication IV are based on data from 621 participants aged 73.6 years (range 65-81 years). Dynamic steady-state balance as measured by average gait speed (habitual and maximal speeds combined) was 1.21 m/s ( $n = 151$ ) at baseline. This is in line with a recent meta-analysis of Hortobágyi et al. (2015), which examined the effects of different types of exercise interventions on gait speed in older adults. The supervised and unsupervised training protocols of the respective studies of Publication IV were comparable in terms of implemented exercises, training periods, training frequencies, and single session durations. This enhances the validity of the results and conclusions of this thesis (for a detailed overview, see Publication IV). The observed effect sizes ( $SMD_{bs}$ ) of Publication IV were small for static/dynamic steady-state balance (0.28/0.35), proactive balance (0.24), and overall balance performance (0.40) compared to medium effect sizes for balance test batteries (0.53) and measures of muscle strength/power (0.51).

These results are partly in accordance with previous systematic reviews/meta-analyses. While there are no reviews available that compare SUP versus UNSUP in healthy older adults, reviews focused on specific patient groups have to be consulted. In respect thereof, our findings are in accordance with a meta-analysis that examined the effects of supervised compared to unsupervised exercise therapy in older patients with intermittent claudication (Fokkenrood et al., 2013). Supervised compared to unsupervised walking and resistance training revealed significant benefits in maximal and pain-free walking distance on a treadmill, with small to medium effect sizes ( $SMD: 0.48$  to  $0.70$ ). The greater effects on gait speed compared to Publication IV might be explained by the younger cohort (i.e., mean age 65.8 years;  $\sim 8$  years younger) of patients with intermittent claudication and by the greater effectiveness of exercise feedback to increase their low baseline gait speed. In line with these findings, Ashworth et al. (2005) confirmed that facility-based compared to home-based exercise interventions (i.e., including balance, resistance, and endurance interventions) are more effective in improving walking distance and time to claudication pain in patients with peripheral vascular disease. However, the effects could not be confirmed in patients with chronic obstructive pulmonary disorder, which suggests that the effects of supervision may be dependent on the specific patient characteristics. In contrast to the presented reviews, Taylor et al. (2015) observed in a recent meta-analysis that in low-risk patients after myocardial infarction, revascularization, or

with heart failure, home- and center-based exercise interventions (i.e., including walking, resistance, and endurance exercises) are equally effective in improving clinical and health-related quality-of-life outcomes (e.g., exercise capacity, blood lipids, blood pressure).

Other reviews and meta-analyses did not directly compare facility- and home-based exercise interventions, but focused on their effects compared with inactive CONs. In this regard, Thiebaud et al. (2014) reported in a systematic review that the effects of partially supervised home-based RT were small compared with supervised facility-based RT programs. Nevertheless, home-based interventions seem to have the potential to increase muscle strength in the elderly (Thiebaud et al., 2014). This corresponds with the findings of this doctoral thesis, in which within-subject SMDs were larger in the supervised training groups. In this regard, Gillespie et al. (2012) reported that multi-component (i.e., mainly CRT) group-based exercise significantly reduced the risk of falling (pooled risk ratio: 0.85) and the rate of falls (pooled rate ratio: 0.71), as did home-based exercise (risk ratio: 0.78; rate ratio: 0.68). However, the distinction between group- and home-based interventions is complicated by the fact that most of the home-based interventions comprised additional sessions that were supervised by an instructor. A direct comparison of the results of Publication IV with the findings of Gillespie et al. (2012) is not possible, since most of the included studies of Publication IV did not report on falls. Additionally, we strongly recommend that future studies clearly differentiate between the location of exercise interventions (e.g., facility-, center-, gym-, or home-based) and the modalities of supervision (e.g., supervised, unsupervised, or combinations) in order to distinguish the effects of both.

*In respect of the findings of Publications III and IV, how does supervision increase exercise intervention outcomes?* Larger adaptations following SUP may be attributed to (1) a higher training intensity due to a higher quality in the execution of exercises and/or a more appropriate exercise progression; (2) a higher training volume due to a better adherence (Stathi, McKenna, & Fox, 2010; Wu et al., 2010); or (3) a beneficial influence on cognitive determinants (e.g., executive function) of physical performance (Forte, Boreham et al., 2013; Forte, Pesce et al., 2013).

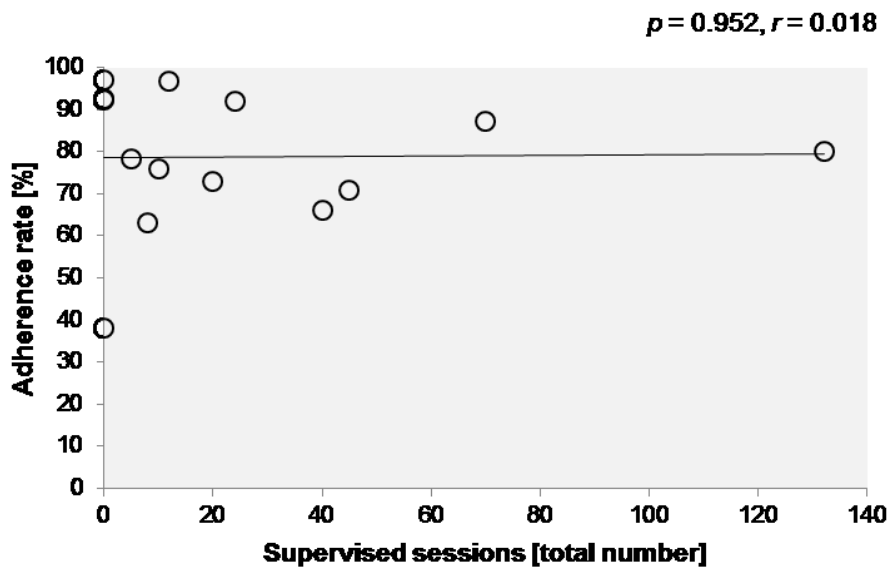
A higher quality in the execution of exercises could imply that participants receiving compared to those not receiving supervision perform the exercises more precisely (i.e., without additional movements), with a larger range of motion, more forcefully, with an appropriate movement velocity, with shorter resting periods, or in other ways that increase exercise intensity. None of the included studies of Publication IV assessed perceived exercise intensity. In



Publication III of this doctoral thesis, participants of SUP and UNSUP reported comparable mean stages of progression in their exercise diaries at the end of the intervention period, indicating a higher perceived intensity in SUP compared to UNSUP. Assuming that participants of unsupervised training programs can achieve similar stages of progression compared with participants of supervised programs, how can exercise supervision influence intensity of the training? To achieve continuous physiological adaptations throughout an exercise intervention, a regular exercise progression is necessary. However, individual person-related performance differences might be responsible for enhanced effects of supervised exercise. For example, participants of UNSUP might introduce the next stage of progression too early, leading to a poor technical execution of the respective exercise and thus a lower intensity. The other way round, if the next stage of progression is introduced too late in UNSUP, the intensity is decreased as well. An experienced exercise supervisor might introduce an appropriate stage of progression of a given exercise at an optimal point in time, considering individual performance differences. Thus, high training intensities can be achieved throughout the intervention period. High training intensities of  $\sim 70\%$  to  $80\%$  1RM produce large effects on measures of muscle strength, as reported by several meta-analyses on dose-response relationships of RT in older adults (Borde et al., 2015; Nicola & Catherine, 2011; Steib et al., 2010). Recommendations concerning the intensities of BT are still lacking.

Another reason for greater exercise adaptations could have been higher adherence rates in SUP groups, resulting in an increased training volume. Adherence to exercise interventions in older adults have been reported to be heterogeneous (Kohler, Kressig, Schindler, & Granacher, 2012). In fact, Stathi et al. (2010) observed that the adherence rate to a 12-month supervised program (93 %) was higher compared to an unsupervised program (85 %), whereas Ashworth and colleagues (2005) reported higher adherence rates for home-based compared to center-based physical activity programs. In Publication III of this thesis, the unsupervised training group (97.4 %) showed a higher training attendance than the supervised group (91.7 %; unsupervised sessions: 94.7%). Including the studies from Publication IV, no significant difference ( $p = 0.658$ ) between SUP ( $80.9 \pm 11.5\%$ ) and UNSUP ( $76.8 \pm 20.8\%$ ) adherence rates was observed. Further, no significant association between adherence rates and the total number of supervised sessions throughout the intervention ( $p = 0.952$ ,  $r = 0.018$ ) was found using the available data of studies of Publication IV (Figure 8). This indicates that there is probably a segment of people who exercise regardless of supervision and a segment of people who will not exercise regardless of the availability of supervision. However, an overestima-

tion of adherence rates in UNSUP due to diary data (e.g., Publication III) could have influenced the low correlation.



**Figure 8:** Association between the adherence rate to training and the total number of supervised sessions within groups. There are 14 data points in the graph because seven of the included studies reported adherence rates for both supervised and unsupervised groups. The association is characterized by  $y = 0.0078x + 78.61$  and  $r^2 = 0.0003$ . Figure published in Publication IV (Lacroix et al., 2017); doi: 10.1007/s40279-017-0747-6

Cognitive aspects may also contribute to the increase of exercise intervention outcomes in SUP compared to UNSUP programs. There is preliminary evidence that executive function plays a role in mediating older adults' improved mobility after an exercise intervention. This hypothesis is reinforced by the small association between improvements in gait speed and leg muscle power (Beijersbergen, Granacher, Vandervoort, DeVita, & Hortobágyi, 2013). Furthermore, recently published studies suggest different mechanisms through which executive function (i.e., inhibition and cognitive flexibility) moderates the role of lower extremity muscle power in determining maximal gait speed of older individuals (Forte, Pesce et al., 2013). It has been concluded that high levels of cognitive flexibility seem necessary to take advantage of leg power for walking at maximal speed (Forte, Pesce et al., 2013). This mechanism may operate depending on the type of intervention, as different types of interventions like multi-component or resistance training might promote executive function through different pathways (i.e., directly through inhibitory capacity; indirectly through enhanced muscle strength) (Forte, Boreham et al., 2013). Supervision may favorably affect such executive functions by providing cognitive challenges, a stimulus that is lacking when exercising without supervi-

sion. In line with this assumption, previous studies reported that a combination of physical and cognitive training maximizes cognitive benefits (Oswald, Gunzelmann, Rupperecht, & Hagen, 2006). The cognitive stimulus could include cognitive processes associated with transportation, scheduling, social interaction, adherence to appointments, and peer pressure. However, the SUP group of Publication III did not show a statistically enhanced performance in executive function (i.e., DSST) compared to the UNSUP group after the training period (i.e., effect size  $d$  pre-post SUP: 0.15; effect size  $d$  pre-post UNSUP: 0.22). The stimuli of supervised exercises are perhaps not limited to the abovementioned factors and include other disregarded aspects. As adherence rates to training and the amount of supervision were not significantly associated (Publication IV), future studies should assess cognitive function and levels of perceived intensity in order to highlight possible reasons for the greater effectiveness of exercising with rather than without supervision.

Despite these speculations about the superiority of SUP, the differences in the improvements between SUP and UNSUP found in Publication IV are relevant from a functional point of view. For example, proxies of static steady-state balance improved on average by 48.7 % in SUP and 16.5 % in UNSUP, amounting to a larger improvement in SUP of 32.2 % ( $SMD_{bs} = 0.28$ ). Further, measures of proactive balance (SUP: 10.1 %, UNSUP: 5.8 %;  $SMD_{bs} = 0.24$ ), balance test batteries (SUP: 3.0 %, UNSUP: 1.8 %;  $SMD_{bs} = 0.53$ ), and measures of muscle strength/power (SUP: 15.8 %, UNSUP: 13.7 %;  $SMD_{bs} = 0.51$ ) revealed net gains for SUP compared to UNSUP of 4.3 %, 1.2 %, and 2.1 %, respectively. In terms of dynamic steady-state balance, SUP increased gait speed (i.e., including habitual and fast gait speed test) from 1.11 m/s to 1.19 m/s by 0.08 m/s. Since UNSUP increased gait speed by 0.03 m/s, the net improvement for SUP compared to UNSUP amounted to 0.05 m/s (4.5 %;  $SMD_{bs} = 0.35$ ). Exclusion of one study that used a tandem walk test as outcome makes this result more unambiguous, revealing a net gain of 0.07 m/s for SUP compared with UNSUP. These net gains are in the range of meaningful changes of gait speed that have been reported in the literature and ranged from 0.04 m/s to 0.14 m/s (Hortobágyi et al., 2015; Perera, Mody, Woodman, & Studenski, 2006). Owing to the healthy and mobile population of older adults observed in Publication IV, an improvement in gait speed of 0.08 m/s in SUP and a net gain of 0.05-0.07 m/s compared with UNSUP can be classified as a clinically meaningful benefit.

However, substantial heterogeneity between studies cannot be excluded, especially for measures of static steady-state balance and muscle strength/power due to high  $I^2$  values of 82 % and 76 %, respectively. With respect to muscle strength/power, three studies tested lower

extremity muscle strength/power by time (e.g., 5CRT), while two studies assessed muscle strength/power by frequency (i.e., 30s CST), which could be an indicator of high  $I^2$  values. Notably, Publication IV revealed the largest effects in favor of SUP for the category balance test batteries (i.e., BBS) and measures of lower extremity muscle strength/power. Comparable effects could be ascribed to the functional overlap of these tests, as the BBS contains subtasks such as chair rises. One possible reason for the observed performance improvements ( $SMD_{ws}$ ) in the UNSUP groups of Publication IV may be that some studies used additional supervised sessions in their UNSUP groups. This assumption is supported by our findings regarding dose-response relationships. Larger effects in favor of SUP programs occurred when compared with UNSUP programs that used no additional supervised sessions. The following paragraph will discuss dose-response relationships of supervision.

An increased number of supervised sessions in SUP did not necessarily reveal larger effects, indicating an inconsistent dose-response relationship. This is not in line with *Hypothesis 6* of this doctoral thesis. Measures of static/dynamic steady-state balance and muscle strength/power showed larger effects for an additional number of 10-29 supervised sessions compared with  $\geq 30$  additional supervised sessions in SUP compared to UNSUP groups. In contrast, proxies of proactive balance, balance test batteries, and overall balance performance revealed larger effects for an additional number of  $\geq 30$  supervised sessions in SUP. Although differences in effects (i.e., between 10-29 and  $\geq 30$  additional supervised sessions in SUP) were small, the findings suggest that there is a threshold of supervision beyond which an additional number of supervised sessions has no beneficial effects. Since only few studies were available for the respective outcome categories, this assumption is limited.

A more consistent result was obtained for the comparison of studies implementing a strictly unsupervised training protocol with studies that implemented supervised sessions in UNSUP. The analyses of Publication IV proved that all outcome categories showed larger effects in favor of SUP for studies with strictly unsupervised groups as comparator ( $0.28 \leq SMD_{bs} \leq 1.24$ ). This superiority of SUP seems to abate when compared with UNSUP that includes an additional, though small number of supervised sessions ( $-0.06 \leq SMD_{bs} \leq 0.41$ ). It might be suggested that exercise supervision is of particular importance for exercises that require an efficient and technically correct execution (i.e., static balance and muscle strength/power), as the difference particularly became apparent for measures of static steady-state balance and muscle strength/power. Apparently, a small number of supervised sessions (average number of supervised sessions in UNSUP containing supervised sessions: 6.7) is sufficient to enhance

balance and muscle strength/power compared to strictly unsupervised programs, yet not to the extent that completely supervised programs do. A crucial point in the differences of SUP compared with UNSUP exercise interventions could be an ineffective exercise execution in strictly unsupervised groups due to the lack of extensive learning of the exercises prior to the training period. The results of Publication III cannot contribute to the discussion regarding dose-response relationships, as the same doses were applied in both SUP and UNSUP. Yet, the participants of UNSUP received an extensive introduction to the exercises, possibly explaining the improvements in some measures (i.e., mainly muscle strength/power).

### **6.5 Limitations of Publications I-IV**

Publication I has some limitations that warrant discussion. First, the participants included in this study were healthy (no history of musculoskeletal, neurological, or orthopedic disorders; mean Mini Mental State Examination score: 28.1), physically active (mean 13.0 h/week) older adults. Thus, the present findings cannot be generalized to other populations (e.g., patients or physically inactive/mobility-limited elderly subjects). Second, Publication I assessed TMS, spinal mobility, and balance performance with specific tests. These measures do not represent all components of muscle strength and balance performance. Other testing situations could have elicited other results, which is why caution is needed when generalizing the present findings to other assessment tools. Third, the applied testing methods are not suitable to explain possible mechanisms behind the significant associations between TMS and static/dynamic steady-state balance. Finally, the findings do not allow for conclusions on cause-and-effects relationships due to the cross-sectional character of the analyses.

Publication III of this thesis also has a few limitations. First, the assessor was not blinded for group allocation. To compensate this limitation and minimize bias, the assessor strictly adhered to a predefined assessment protocol (including the exact wording) and gave the same instructions to every participant without any feedback on performance. Second, due to methodological constraints (e.g., no electrophysiological tests and imaging techniques), this study cannot elucidate adaptations in the central nervous and neuromuscular systems. Third, the examined population of Publication III was classified as healthy and physically active. Thus, our study findings cannot be generalized to patients and sedentary cohorts. Finally, this study examined intrinsic risk factors for falls and not the number of falls or fall rate. Our program could still be a helpful tool for fall prevention in older adults, considering the fact that CST, SAT, and SDT were improved above limits which mark an increased fall risk in both SUP and

UNSUP (limits: CST  $\geq$  12 s; SAT/SDT  $\geq$  5 s) and that SUP additionally improved above the limit in ROM (10-19 s) (Granacher, Muehlbauer et al., 2014).

Concerning the study protocol (Publication II), some of the intended ideas could not be realized in Publication III. The minor deviations affect the (1) assessments, (2) training, and (3) statistical analyses. In terms of assessments, some of the intended tests could not be applied due to feasibility issues (e.g., time constraints). Handgrip strength and MMSE were only measured at baseline. However, the DSST was used as a test of executive function at pre, post and follow-up, based on the recommendation of an expert in the field (Sport Psychologist). Further, performance in the tuning fork test and the FES-I were designated as exclusion criteria. This was not feasible, which is why the MMSE and the CDT were used. Regarding balance assessment, stride width could not be measured due to technical constraints. Regarding muscle power performance, counter movement jumps were not conducted. Based on preliminary trials of counter movement jumps in elderly subjects, a safe and appropriate implementation of the task was not feasible. Finally, the outcome METs per week were not reported for the Freiburg questionnaire of physical activity, as the results were equivalent to the variable of hours/week. Regarding the training protocol, some minor changes compared to the study protocol occurred. Originally, the participants of UNSUP were to perform a short version of the SUP in order to elicit the (a) effects of supervision and (b) dose-response relationships of exercise. However, in preparation for the RCT we decided to put more emphasis on the effects of supervision, which is why the number of exercises in the UNSUP was adjusted according to the SUP (i.e., “3 times 5” instead of “3 times 3”). In terms of the implementation of the program into clinical practice, this is of advantage, because in cases where a supervised implementation is not possible (i.e., high costs, mobility problems, time constraints), the UNSUP can be implemented equivalently without loss of training volume. In addition, the range of intended perceived exertion measured with the Borg scale was raised (i.e., from 10-16 to 12-16) in order to ensure a preferably high training intensity. Another deviation was that weekly phone-calls were not feasible and biweekly phone calls were conducted. Statistical analyses were slightly changed in as much as we considered a higher drop-out rate in our a-priori power analysis. Thus, a larger total sample was recruited. An original idea of the study protocol was to validate clinical balance and muscle power tests with the corresponding instrumented tests. However, these analyses are planned to be conducted at a future date and are not part of the results discussed in Publication III. Finally, the initially intended evaluation of the prevalence of sarcopenia was not possible due to the high performance levels of partici-

pants regarding the respective tests (i.e., habitual gait speed, handgrip strength, and muscle mass). The primary aim of the study protocol was to facilitate implementation into clinical practice by providing an easy reproducible practice guide. Of note, the training protocol was applied as proposed in Publication III.

Publication IV has several limitations, too. First, only a small number of studies could be included in the meta-analysis, making the conclusions preliminary. Second, nine of the 11 included studies did not blind the assessors and seven of the 11 included studies did use a concealed allocation. The beneficial effects of SUP may have been overestimated, since studies without adequate allocation concealment tend to exaggerate treatment effects compared with those with adequate concealment (Pildal et al., 2007). However, the probability of biased conclusions is minimized by the fact that most of the funnel plots were symmetrical. Third, we observed the lack of a consistent set of balance and muscle strength/power tests in the literature. Such a consistent assessment tools is essential for future studies in order to conduct more comprehensive meta-analyses. Fourth, a clear terminology for ‘supervised’ or ‘unsupervised’ exercise interventions is lacking. Actually, some UNSUP groups contained supervised sessions, which may have biased the results. Fourth, regarding the analysis of dose-response relationships, we indirectly compared  $SMD_{bs}$  across studies and not within a single controlled study, limiting its validity. Finally, our findings are relevant to reductions in fall risk but not directly to reductions in the number and rate of falls.

## 7. Conclusions

This doctoral thesis contains four Publications that investigate factors potentially influencing the effectiveness of BT and RT in older adults. The aggregation of the four publications leads to the following main results:

- a) Measures of TMS and static steady-state balance as well as specific measures of TMS and dynamic steady-state balance are significantly correlated in older adults. In addition, spinal mobility and balance performance showed non-significant correlations and seem to be independent of each other.
- b) CRT (supervised and unsupervised) is a safe and feasible exercise intervention that positively influences important intrinsic fall risk factors in healthy older adults.
- c) Supervised CRT causes larger effects than unsupervised CRT in improving healthy older adults' balance and muscle power.
- d) Improvements of balance and muscle power following CRT are stable. After a 12-week detraining period, most of the variables remained above baseline values in healthy older adults.
- e) Regarding the overall effects of supervision on various types of exercise interventions (i.e., BT, RT, and CRT), a meta-analysis revealed that SUP are superior compared to UNSUP in improving measures of balance and muscle strength/power in older adults.
- f) Effects in favor of SUP are more pronounced when compared to strict versions of UNSUP instead of UNSUP with a small number of supervised sessions.

The main results of the current doctoral thesis lead to several practical implications that are presented in the following chapter.



## 8. Practical implications and future directions

Publication I of this thesis revealed significant associations between TMS and static/dynamic steady-state balance. Therefore, gains made in TMS after RT may be associated with a change in static and dynamic steady-state balance performance, which is why TMS-promoting exercises could be integrated in RT programs for older adults as an adjunct to traditional RT exercises (i.e., lower extremity resistance exercises). In addition, spinal mobility and balance performance seem to be independent of each other and may have to be tested and trained separately in a complementary way.

Based on high adherence rates to training, low dropout rates throughout the intervention period, and no training-related injuries, the CRT program presented in Publications II and III may be implemented into clinical practice to mitigate important intrinsic fall risk factors in healthy older adults. Although performance improvements proved to be relatively stable over a 12-week period, it is suggested that CRT should be conducted permanently to avoid performance decrements after longer periods of training cessation.

Publications III and IV revealed that supervised compared to unsupervised regimens cause larger effects in improving older adults' balance and muscle strength/power performance. Given these findings, supervised sessions should be integrated in fall-preventive exercise interventions, if possible. According to the applied protocol in Publication III and the most frequently implemented training frequency in the literature, we recommend BT and/or RT programs with three sessions per week, with two of these sessions being supervised by professional staff in order to achieve optimal and clinically relevant effects. If circumstances (e.g., resource constraints, financial problems, mobility/transportation problems, lack of motivation) do not permit supervised training sessions, completely or partly unsupervised exercise interventions are still an option to improve balance and muscle strength/power performance in the elderly. Future RCTs with a high methodological quality should evaluate graded intervention approaches by implementing different stages of exercise supervision (i.e., all sessions supervised vs. a lower number of sessions supervised vs. no sessions supervised), and include measures of executive function and perceived exercise intensity to get a clearer picture of the role of supervision and possible reasons behind it.

The results of Publications I to IV contribute to already existing practical recommendations (e.g., Borde et al., 2015; Granacher, Muehlbauer et al., 2014; Lesinski et al., 2015b) and can be directly applied by a wide range of professions, including sport scientists, physiotherapists, geriatricians, and other practitioners. Since BT and RT interventions are applied both sepa-

rately and combined in practice, general recommendations concerning every training characteristic are hard to derive. Furthermore, previous reviews examining dose-response relationships of BT and RT indirectly compared training characteristics across studies and not within single controlled studies. Other authors provided separate recommendations for BT and RT. However, since the emphasis of Publications II and III of this thesis was placed on CRT and most of the studies of Publications IV used a CRT, the following recommendations are designed for exercise interventions that aim at enhancing older adults' balance and muscle strength/power performance. Based on our findings and existing meta-analyses, recommendations regarding the main characteristics of such programs can be put forward (Table 1). In order to achieve larger effects in BT or RT alone, other modalities may be more effective (Borde et al., 2015; Lesinski et al., 2015b).

**Table 1:** Recommended main modalities for improving balance and muscle strength/power in older adults (based on Borde et al., 2015; Lesinski et al., 2015b; Publication III; Publication IV).

<b>Exercise/training modality</b>	<b>Recommendation</b>
Type of exercises	Balance (static/dynamic steady-state, proactive, and reactive) and lower extremity/trunk resistance (muscle strength and power) exercises
Training period (weeks)	at least 11
Frequency (sessions per week)	3
Single session duration (minutes)	45
Sets per exercise	2-4
Rest between sets (seconds)	30-120*
Intensity	Resistance training with own body weight: Perceived exertion on the Borg scale of 12-16 ('somewhat hard' to 'hard') Balance training: no scale available
<b>Amount of supervision</b>	<b>at least 2 out of 3 sessions supervised</b>

\*due to a lower muscular fatigue, shorter resting periods may be applied in balance training compared to resistance training (i.e., 30 seconds)

This doctoral thesis also offers the basis for future research projects in the field of BT and RT in older adults. Even though the thesis attempted to fill the recognized gaps in the literature regarding influencing factors of BT and RT in older adults following a comprehensive ap-

proach, some important issues remain unresolved. To fill the gaps in the current literature, future studies should approach the following issues:

- a) The investigation of cause-and-effect relationships between TMS and balance performance by conducting longitudinal studies that examine the impact of trunk RT on measures of balance performance in the elderly. Studies should especially focus on the benefits of programs that implement trunk exercises compared to programs that implement only lower extremity exercises.
- b) The impact of fall-preventive CRT programs in high-risk populations (e.g., older adults with mobility deficits, physically inactive, institutionalized persons). Since the conclusions of Publication III as well as Publication IV of this doctoral thesis is limited to mainly active, healthy older adults, future high-quality RCTs should focus on the aforementioned populations. Recent large-scale studies additionally demonstrated the importance of non-exercise falls prevention tools in adjunct to exercise-based programs, especially for frail and mobility-limited elderly (Albert & King, 2017). Such non-exercise-based contents may indirectly influence physical ability and fall risk through greater social engagement and increased activity, for example (Albert & King, 2017).
- c) The application of graded, high-quality RCTs that directly compare different levels of supervision (i.e., maximum dose vs. medium dose vs. minimum dose vs. control). Thereby, clear dose-response relationships of exercise supervision could be established.
- d) The assessment of cognitive function and perceived exercise intensity in RCTs investigating the role of supervision in order to elicit possible reasons for the effects of supervision.
- e) The inclusion of cost-effectiveness analyses to facilitate decisions for funders in the appraisal of future projects.
- f) The inclusion of the number of falls as a main outcome in RCTs that examine the role of supervision in order to permit conclusions regarding falls. Most of the previous studies' conclusions are limited to the risk of falling, like the conclusions of the present thesis, which focused on intrinsic fall risk factors.

With reference to the 'sequence of prevention'-model of injuries by van Mechelen et al. (van Mechelen, Hlobil, & Kemper, 1992), a health-care problem has to be identified and described

in terms of incidence and severity in a first step. Thereafter, the factors and mechanisms which play a role in the occurrence of the problem have to be identified (step 2; etiology). The third step is to introduce measures that have preventive potential in terms of risk reduction. This step should be based on the second step (etiology and mechanisms). Finally, the effect of the measures on the initial problem must be evaluated by repeating the first step (van Mechelen et al., 1992). In this model, the present doctoral thesis matches step #3. With our findings, effects of the investigated exercise programs regarding intrinsic (person-related) fall risk factors have been proven and as a consequence, step 4 can now be initiated. An epidemiological approach with a larger number of participants should be planned and realized that clearly focuses on fall rate as primary endpoint. Usually a high number of participants is needed to achieve appropriate statistical power when assessing the number of falls in such programs. However, recent publications point to the widespread feasibility of such approaches by including facilities like senior centers, churches, nursing homes, and assisted living centers (Albert & King, 2017).

## 9. References

- Aagaard, P., Suetta, C., Caserotti, P., Magnusson, S. P., & Kjaer, M. (2010). Role of the nervous system in sarcopenia and muscle atrophy with aging: strength training as a countermeasure. *Scandinavian journal of medicine & science in sports*, 20(1), 49–64. <https://doi.org/10.1111/j.1600-0838.2009.01084.x>
- Aartolahti, E., Haekkinen, A., Loennroos, E., Kautiainen, H., Sulkava, R., & Hartikainen, S. (2013). Relationship between functional vision and balance and mobility performance in community-dwelling older adults. *Aging clinical and experimental research*, 25(5), 545–552. <https://doi.org/10.1007/s40520-013-0120-z>
- Aboutorabi, A., Arazpour, M., Bahramizadeh, M., Hutchins, S. W., & Fadayeveatan, R. (2016). The effect of aging on gait parameters in able-bodied older subjects: A literature review. *Aging clinical and experimental research*, 28(3), 393–405. <https://doi.org/10.1007/s40520-015-0420-6>
- Abrahamova, D., & Hlavacka, F. (2008). Age-related changes of human balance during quiet stance. *Physiological research*, 57(6), 957–964.
- Akuthota, V., Ferreiro, A., Moore, T., & Fredericson, M. (2008). Core stability exercise principles. *Current Sports Medicine Reports*, 7(1), 39–44. <https://doi.org/10.1097/01.CSMR.0000308663.13278.69>
- Akuthota, V., & Nadler, S. F. (2004). Core strengthening. *Archives of Physical Medicine & Rehabilitation*, 85(3 Suppl 1), S86-92.
- Albert, S. M., & King, J. (2017). Effectiveness of statewide falls prevention efforts with and without group exercise. *Preventive Medicine*, 105, 5–9. <https://doi.org/10.1016/j.ypmed.2017.08.010>
- Almeida, T. L., Alexander, N. B., Nyquist, L. V., Montagnini, M. L., Santos, A. C., Rodrigues, G. H., . . . Wajngarten, M. (2013). Minimally supervised multimodal exercise to reduce falls risk in economically and educationally disadvantaged older adults. *Journal of Aging and Physical Activity*, 21(3), 241–259.
- Alway, S. E., Mohamed, J. S., & Myers, M. J. (2017). Mitochondria Initiate and Regulate Sarcopenia. *Exercise and Sport Sciences Reviews*, 45(2), 58–69. <https://doi.org/10.1249/JES.0000000000000101>
- Amiridis, I. G., Hatzitaki, V., & Arabatzi, F. (2003). Age-induced modifications of static postural control in humans. *Neuroscience Letters*, 350(3), 137–140.
- Anderson, L. J., Erceg, D. N., & Schroeder, E. T. (2012). Utility of multifrequency bioelectrical impedance compared with dual-energy x-ray absorptiometry for assessment of total and regional body composition varies between men and women. *Nutrition research*, 32(7), 479–485. <https://doi.org/10.1016/j.nutres.2012.05.009>
- Angermeyer, M. C., Kilian, R., & Matschinger, H. (2000). *[WHOQOL-100 und WHOQOL-BREF: Handbuch für die deutschsprachige Version der WHO-Instrumente zur Erfassung von Lebensqualität]*. Göttingen: Hogrefe & Huber.
- Aruin, A. S., & Latash, M. L. (1995). Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. *Experimental Brain Research*, 103(2), 323–332.
- Ashworth, N. L., Chad, K. E., Harrison, E. L., Reeder, B. A., & Marshall, S. C. (2005). Home versus center based physical activity programs in older adults. *The Cochrane database of systematic reviews*, CD004017. <https://doi.org/10.1002/14651858.CD004017.pub2>

- Avlund, K., Schroll, M., Davidsen, M., Løvborg, B., & Rantanen, T. (1994). Maximal isometric muscle strength and functional ability in daily activities among 75-year-old men and women. *Scandinavian Journal of Medicine & Science in Sports*, 4(1), 32–40. <https://doi.org/10.1111/j.1600-0838.1994.tb00403.x>
- Bak, P., Anders, C., Bocker, B., & Smolenski, U. C. (2003). Reliability of the measurement of isometric maximal voluntary contraction of trunk muscles in healthy subjects. *Physikalische Medizin, Rehabilitationsmedizin, Kurortmedizin*, 13(1), 28–34.
- Ballard, J. E., McFarland, C., Wallace, L. S., Holiday, D. B., & Roberson, G. (2004). The effect of 15 weeks of exercise on balance, leg strength, and reduction in falls in 40 women aged 65 to 89 years. *Journal of the American Medical Women's Association (1972)*, 59(4), 255–261.
- Balogun, J. A., Olokungbemi, A. A., & Kuforiji, A. R. (1992). Spinal mobility and muscular strength: Effects of supine- and prone-lying back extension exercise training. *Archives of Physical Medicine & Rehabilitation*, 73(8), 745–751.
- Barreiro, E., Coronell, C., Laviña, B., Ramírez-Sarmiento, A., Orozco-Levi, M., & Gea, J. (2006). Aging, sex differences, and oxidative stress in human respiratory and limb muscles. *Free radical biology & medicine*, 41(5), 797–809. <https://doi.org/10.1016/j.freeradbiomed.2006.05.027>
- Bean, J. F., Kiely, D. K., LaRose, S., Alian, J., & Frontera, W. R. (2007). Is stair climb power a clinically relevant measure of leg power impairments in at-risk older adults? *Archives of Physical Medicine and Rehabilitation*, 88(5), 604–609. <https://doi.org/10.1016/j.apmr.2007.02.004>
- Behm, D. G., Drinkwater, E. J., Willardson, J. M., & Cowley, P. M. (2010). The use of instability to train the core musculature. *Applied physiology, nutrition, and metabolism*, 35(1), 91–108. <https://doi.org/10.1139/H09-127>
- Beijersbergen, C. M. I., Granacher, U., Vandervoort, A. A., DeVita, P., & Hortobágyi, T. (2013). The biomechanical mechanism of how strength and power training improves walking speed in old adults remains unknown. *Ageing Research Reviews*, 12(2), 618–627. <https://doi.org/10.1016/j.arr.2013.03.001>
- Beijersbergen, C. M. I., Granacher, U., Gaebler, M., Devita, P., & Hortobágyi, T. (2017a). Kinematic Mechanisms of How Power Training Improves Healthy Old Adults' Gait Velocity. *Medicine and Science in Sports and Exercise*, 49(1), 150–157. <https://doi.org/10.1249/MSS.0000000000001082>
- Beijersbergen, C. M. I., Granacher, U., Gaebler, M., Devita, P., & Hortobágyi, T. (2017b). Hip mechanics underlie lower extremity power training-induced increase in old adults' fast gait velocity: The Potsdam Gait Study (POGS). *Gait & Posture*, 52, 338–344. <https://doi.org/10.1016/j.gaitpost.2016.12.024>
- Beijersbergen, C. M. I., Hortobágyi, T., Beurskens, R., Lenzen-Grossimlinghaus, R., Gaebler, M., & Granacher, U. (2016). Effects of Power Training on Mobility and Gait Biomechanics in Old Adults with Moderate Mobility Disability: Protocol and Design of the Potsdam Gait Study (POGS). *Gerontology*, 62(6), 597–603. <https://doi.org/10.1159/000444752>
- Bergmark, A. (1989). Stability of the lumbar spine. A study in mechanical engineering. *Acta orthopaedica Scandinavica. Supplementum*, 230, 1–54.

- Bettcher, B. M., Libon, D. J., Kaplan, E., Swenson, R., & Penney, D. L. (2011). Digit Symbol Substitution Test. In J. S. Kreutzer, J. DeLuca, & B. Caplan (Eds.), *Encyclopedia of Clinical Neuropsychology* (pp. 849–853). New York, NY: Springer New York. [https://doi.org/10.1007/978-0-387-79948-3\\_1289](https://doi.org/10.1007/978-0-387-79948-3_1289)
- Bohannon, R. W. (2006). Reference values for the timed up and go test: a descriptive meta-analysis. *Journal of geriatric physical therapy*, *29*(2), 64–68.
- Bohannon, R. W., & Williams Andrews, A. (2011). Normal walking speed: a descriptive meta-analysis. *Physiotherapy*, *97*(3), 182–189. <https://doi.org/10.1016/j.physio.2010.12.004>
- Borde, R., Hortobágyi, T., & Granacher, U. (2015). Dose-Response Relationships of Resistance Training in Healthy Old Adults: A Systematic Review and Meta-Analysis. *Sports medicine (Auckland, N.Z.)*, *45*(12), 1693–1720. <https://doi.org/10.1007/s40279-015-0385-9>
- Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise*, *14*(5), 377–381.
- Bosco, C., & Komi, P. V. (1980). Influence of aging on the mechanical behavior of leg extensor muscles. *European Journal of Applied Physiology and Occupational Physiology*, *45*(2-3), 209–219.
- Boshuizen, H. C., Stemmerik, L., Westhoff, M. H., & Hopman-Rock, M. (2005). The effects of physical therapists' guidance on improvement in a strength-training program for the frail elderly. *Journal of Aging and Physical Activity*, *13*(1), 5–22.
- Brown, W. F. (1972). A method for estimating the number of motor units in thenar muscles and the changes in motor unit count with ageing. *Journal of neurology, neurosurgery, and psychiatry*, *35*(6), 845–852.
- Bullain, S. S., Corrada, M. M., Shah, B. A., Mozaffar, F. H., Panzenboeck, M., & Kawas, C. H. (2013). Poor physical performance and dementia in the oldest old: The 90+ study. *JAMA neurology*, *70*(1), 107–113. <https://doi.org/10.1001/jamaneurol.2013.583>
- Bunout, D., Barrera, G., Avendano, M., La Maza, P. de, Gattas, V., Leiva, L., & Hirsch, S. (2005). Results of a community-based weight-bearing resistance training programme for healthy Chilean elderly subjects. *Age and Ageing*, *34*(1), 80–83. <https://doi.org/10.1093/ageing/afi005>
- Burns, P. B., Rohrich, R. J., & Chung, K. C. (2011). The levels of evidence and their role in evidence-based medicine. *Plastic and Reconstructive Surgery*, *128*(1), 305. <https://doi.org/10.1097/PRS.0b013e318219c171>
- Callisaya, M. L., Blizzard, L., Schmidt, M. D., McGinley, J. L., & Srikanth, V. K. (2010). Ageing and gait variability--a population-based study of older people. *Age and Ageing*, *39*(2), 191–197. <https://doi.org/10.1093/ageing/afp250>
- Campbell, A. J., Borrie, M. J., & Spears, G. F. (1989). Risk factors for falls in a community-based prospective study of people 70 years and older. *Journal of gerontology*, *44*(4), M112-7.
- Campbell, A. J., & Robertson, M. C. (2007). Rethinking individual and community fall prevention strategies: a meta-regression comparing single and multifactorial interventions. *Age and Ageing*, *36*(6), 656–662. <https://doi.org/10.1093/ageing/afm122>
- Campbell, A. J., Robertson, M. C., Gardner, M. M., Norton, R. N., Tilyard, M. W., & Buchner, D. M. (1997). Randomised controlled trial of a general practice programme of home based exercise to prevent falls in elderly women. *BMJ*, *315*(7115), 1065–1069.

- Carvalho, M. J., Marques, E., & Mota, J. (2009). Training and detraining effects on functional fitness after a multicomponent training in older women. *Gerontology*, *55*(1), 41–48. <https://doi.org/10.1159/000140681>
- Christie, J. (2011). Progressive resistance strength training for improving physical function in older adults. *International journal of older people nursing*, *6*(3), 244–246. <https://doi.org/10.1111/j.1748-3743.2011.00291.x>
- Clemson, L., Singh, M. A. F., Bundy, A., Cumming, R. G., Manollaras, K., O'Loughlin, P., & Black, D. (2012). Integration of balance and strength training into daily life activity to reduce rate of falls in older people (the LiFE study): randomised parallel trial. *BMJ*, *345*(e4547). <https://doi.org/10.1136/bmj.e4547>
- Cohen, J. (1992). A power primer. *Psychological bulletin*, *112*(1), 155–159.
- Cohen-Mansfield, J., Marx, M. S., & Guralnik, J. M. (2003). Motivators and barriers to exercise in an older community-dwelling population. *Journal of Aging and Physical Activity*, *11*, 242–253.
- Connelly, D. M., Rice, C. L., Roos, M. R., & Vandervoort, A. A. (1999). Motor unit firing rates and contractile properties in tibialis anterior of young and old men. *Journal of applied physiology (Bethesda, Md. : 1985)*, *87*(2), 843–852.
- Cresswell, A. G., Oddsson, L., & Thorstensson, A. (1994). The influence of sudden perturbations on trunk muscle activity and intra-abdominal pressure while standing. *Experimental Brain Research*, *98*(2), 336–341.
- Csuka, M., & McCarty, D. J. (1985). Simple method for measurement of lower extremity muscle strength. *The American journal of medicine*, *78*(1), 77–81.
- Cyarto, E. V., Brown, W. J., Marshall, A. L., & Trost, S. G. (2008a). Comparison of the effects of a home-based and group-based resistance training program on functional ability in older adults. *American Journal of Health Promotion*, *23*(1), 13–17. <https://doi.org/10.4278/ajhp.07030120>
- Cyarto, E. V., Brown, W. J., Marshall, A. L., & Trost, S. G. (2008b). Comparative effects of home- and group-based exercise on balance confidence and balance ability in older adults: cluster randomized trial. *Gerontology*, *54*(5), 272–280. <https://doi.org/10.1159/000155653>
- Davis, J. C., Robertson, M. C., Ashe, M. C., Liu-Ambrose, T., Khan, K. M., & Marra, C. A. (2010). Does a home-based strength and balance programme in people aged or =80 years provide the best value for money to prevent falls? A systematic review of economic evaluations of falls prevention interventions. *British journal of sports medicine*, *44*(2), 80–89. <https://doi.org/10.1136/bjism.2008.060988>
- Day, L., Fildes, B., Gordon, I., Fitzharris, M., Flamer, H., & Lord, S. (2002). Randomised factorial trial of falls prevention among older people living in their own homes. *BMJ*, *325*(7356), 128–131. <https://doi.org/10.1136/bmj.325.7356.128>
- Dias, N., Kempen, G. I. J. M., Todd, C. J., Beyer, N., Freiburger, E., Piot-Ziegler, C., . . . Hauer, K. (2006). [The German version of the Falls Efficacy Scale-International Version (FES-I)]. *Zeitschrift für Gerontologie und Geriatrie*, *39*(4), 297–300. <https://doi.org/10.1007/s00391-006-0400-8>
- Doherty, T. J., Vandervoort, A. A., Taylor, A. W., & Brown, W. F. (1993). Effects of motor unit losses on strength in older men and women. *Journal of applied physiology (Bethesda, Md. : 1985)*, *74*(2), 868–874.
- Donat, H., & Oezcan, A. (2007). Comparison of the effectiveness of two programmes on older adults at risk of falling: unsupervised home exercise and supervised group exercise. *Clinical Rehabilitation*, *21*(3), 273–283. <https://doi.org/10.1177/0269215506069486>



- Duncan, P. W., Weiner, D. K., Chandler, J., & Studenski, S. (1990). Functional reach: A new clinical measure of balance. *Journals of Gerontology*, 45(6), M192-7.
- Edström, E., Altun, M., Bergman, E., Johnson, H., Kullberg, S., Ramírez-León, V., & Ulfhake, B. (2007). Factors contributing to neuromuscular impairment and sarcopenia during aging. *Physiology & Behavior*, 92(1-2), 129–135. <https://doi.org/10.1016/j.physbeh.2007.05.040>
- Ellis, P. D. (2011). *The essential guide to effect sizes: Statistical power, meta-analysis, and the interpretation of research results* (reprint). Cambridge: Cambridge Univ. Press.
- Era, P., Sainio, P., Koskinen, S., Haavisto, P., Vaara, M., & Aromaa, A. (2006). Postural balance in a random sample of 7,979 subjects aged 30 years and over. *Gerontology*, 52(4), 204–213. <https://doi.org/10.1159/000093652>
- Evans, W. J., & Cyr-Campbell, D. (1997). Nutrition, exercise, and healthy aging. *Journal of the American Dietetic Association*, 97(6), 632–638. [https://doi.org/10.1016/S0002-8223\(97\)00160-0](https://doi.org/10.1016/S0002-8223(97)00160-0)
- Fiatarone, M. A., Marks, E. C., Ryan, N. D., Meredith, C. N., Lipsitz, L. A., & Evans, W. J. (1990). High-intensity strength training in nonagenarians. Effects on skeletal muscle. *Jama*, 263(22), 3029–3034.
- Fielding, R. A., LeBrasseur, N. K., Cuoco, A., Bean, J., Mizer, K., & Fiatarone Singh, M. A. (2002). High-velocity resistance training increases skeletal muscle peak power in older women. *Journal of the American Geriatrics Society*, 50(4), 655–662.
- Fokkenrood, H. J. P., Bendermacher, B. L. W., Lauret, G. J., Willigendael, E. M., Prins, M. H., & Teijink, J. A. W. (2013). Supervised exercise therapy versus non-supervised exercise therapy for intermittent claudication. *The Cochrane Library*, 8, CD005263.
- Foldvari, M., Clark, M., Laviolette, L. C., Bernstein, M. A., Kaliton, D., Castaneda, C., . . . Singh, M. A. (2000). Association of muscle power with functional status in community-dwelling elderly women. *The journals of gerontology. Series A, Biological sciences and medical sciences*, 55(4), M192-9.
- Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *Journal of psychiatric research*, 12(3), 189–198.
- Forte, R., Boreham, C. A., Leite, J. C., Vito, G. de, Brennan, L., Gibney, E. R., & Pesce, C. (2013). Enhancing cognitive functioning in the elderly: multicomponent vs resistance training. *Clinical Interventions in Aging*, 8, 19–27. <https://doi.org/10.2147/CIA.S36514>
- Forte, R., Pesce, C., Leite, J. C., Vito, G. de, Gibney, E. R., Tomporowski, P. D., & Boreham, C. A. (2013). Executive function moderates the role of muscular fitness in determining functional mobility in older adults. *Aging clinical and experimental research*, 25(3), 291–298. <https://doi.org/10.1007/s40520-013-0044-7>
- Franco, M. R., Howard, K., Sherrington, C., Ferreira, P. H., Rose, J., Gomes, J. L., & Ferreira, M. L. (2015). Eliciting older people's preferences for exercise programs: a best-worst scaling choice experiment. *Journal of Physiotherapy*, 61(1), 34–41. <https://doi.org/10.1016/j.jphys.2014.11.001>
- Freiberger, E., Blank, W. A., Salb, J., Geilhof, B., Hentschke, C., Landendoerfer, P., . . . Siegrist, M. (2013). Effects of a complex intervention on fall risk in the general practitioner setting: a cluster randomized controlled trial. *Clinical Interventions in Aging*, 8, 1079–1088. <https://doi.org/10.2147/cia.s46218>

- Frey, I., Berg, A., Grathwohl, D., & Keul, J. (1999). [Freiburg Questionnaire of physical activity--development, evaluation and application]. *Sozial- und Praventivmedizin*, *44*(2), 55–64.
- Frontera, W. R., Hughes, V. A., Fielding, R. A., Fiatarone, M. A., Evans, W. J., & Roubenoff, R. (2000). Aging of skeletal muscle: a 12-yr longitudinal study. *Journal of applied physiology (Bethesda, Md. : 1985)*, *88*(4), 1321–1326.
- Frontera, W. R., Hughes, V. A., Lutz, K. J., & Evans, W. J. (1991). A cross-sectional study of muscle strength and mass in 45- to 78-yr-old men and women. *Journal of applied physiology (Bethesda, Md. : 1985)*, *71*(2), 644–650.
- Frontera, W. R., Meredith, C. N., O'Reilly, K. P., & Evans, W. J. (1990). Strength training and determinants of VO<sub>2</sub>max in older men. *Journal of applied physiology (Bethesda, Md. : 1985)*, *68*(1), 329–333.
- Gianoudis, J., Bailey, C. A., Ebeling, P. R., Nowson, C. A., Sanders, K. M., Hill, K., & Daly, R. M. (2014). Effects of a targeted multimodal exercise program incorporating high-speed power training on falls and fracture risk factors in older adults: a community-based randomized controlled trial. *Journal of Bone and Mineral Research*, *29*(1), 182–191. <https://doi.org/10.1002/jbmr.2014>
- Gill, T. M., Allore, H. G., Holford, T. R., & Guo, Z. (2004). Hospitalization, restricted activity, and the development of disability among older persons. *Jama*, *292*(17), 2115–2124. <https://doi.org/10.1001/jama.292.17.2115>
- Gillespie, L. D., Robertson, M. C., Gillespie, W. J., Sherrington, C., Gates, S., Clemson, L. M., & Lamb, S. E. (2012). Interventions for preventing falls in older people living in the community. *The Cochrane database of systematic reviews*, *9*, Cd007146. <https://doi.org/10.1002/14651858.CD007146.pub3>
- Godde, B., & Voelcker-Rehage, C. (2017). Cognitive Resources Necessary for Motor Control in Older Adults Are Reduced by Walking and Coordination Training. *Frontiers in human neuroscience*, *11*, 156. <https://doi.org/10.3389/fnhum.2017.00156>
- Godlee, F. (2001). Publishing study protocols: Making them visible will improve registration, reporting and recruitment. *BMC news and views*, *2*(4).
- Granacher, U., Gollhofer, A., Hortobagyi, T., Kressig, R. W., & Muehlbauer, T. (2013). The importance of trunk muscle strength for balance, functional performance, and fall prevention in seniors: a systematic review. *Sports medicine (Auckland, N.Z.)*, *43*(7), 627–641. <https://doi.org/10.1007/s40279-013-0041-1>
- Granacher, U., Gollhofer, A., & Strass, D. (2006). Training induced adaptations in characteristics of postural reflexes in elderly men. *Gait & Posture*, *24*(4), 459–466. <https://doi.org/10.1016/j.gaitpost.2005.12.007>
- Granacher, U., Gruber, M., & Gollhofer, A. (2009). [The impact of sensorimotor training on postural control in elderly men]. *Deutsche Zeitschrift fur Sportmedizin*, *60*(12), 387–393.
- Granacher, U., Gruber, M., & Gollhofer, A. (2010). Force production capacity and functional reflex activity in young and elderly men. *Aging clinical and experimental research*, *22*(5-6), 374–382. <https://doi.org/10.3275/6706>
- Granacher, U., Gruber, M., Strass, D., & Gollhofer, A. (2007). The impact of sensorimotor training in elderly men on maximal and explosive force production capacity. *Deutsche Zeitschrift fur Sportmedizin*, *58*(12), 446–451.

- Granacher, U., Muehlbauer, T., Bridenbaugh, S., Bleiker, E., Wehrle, A., & Kressig, R. W. (2010). Balance training and multi-task performance in seniors. *International journal of sports medicine*, *31*(5), 353–358. <https://doi.org/10.1055/s-0030-1248322>
- Granacher, U., Muehlbauer, T., Bridenbaugh, S., Wehrle, A., & Kressig, R. W. (2010). [Age-related differences during single and multi-task walking]. *Deutsche Zeitschrift für Sportmedizin*, *61*(11), 258–263.
- Granacher, U., Muehlbauer, T., Gschwind, Y. J., Pfenninger, B., & Kressig, R. W. (2014). [Assessment and training of strength and balance for fall prevention in the elderly: recommendations of an interdisciplinary expert panel]. *Zeitschrift für Gerontologie und Geriatrie*, *47*(6), 513–526. <https://doi.org/10.1007/s00391-013-0509-5>
- Granacher, U., Bridenbaugh, S. A., Muehlbauer, T., Wehrle, A., & Kressig, R. W. (2011). Age-related effects on postural control under multi-task conditions. *Gerontology*, *57*(3), 247–255. <https://doi.org/10.1159/000322196>
- Granacher, U., Lacroix, A., Roettger, K., Gollhofer, A., & Muehlbauer, T. (2014). Relationships between trunk muscle strength, spinal mobility, and balance performance in older adults. *Journal of Aging & Physical Activity*, *22*(4), 490–498. <https://doi.org/10.1123/japa.2013-0108>
- Granacher, U., Muehlbauer, T., Gollhofer, A., Kressig, R. W., & Zahner, L. (2011). An Intergenerational Approach in the Promotion of Balance and Strength for Fall Prevention - A Mini-Review. *Gerontology*, *57*(4), 304–315. <https://doi.org/10.1159/000320250>
- Granacher, U., Muehlbauer, T., & Gruber, M. (2012). A qualitative review of balance and strength performance in healthy older adults: Impact for testing and training. *Journal of aging research*, *2012*, 708905. <https://doi.org/10.1155/2012/708905>
- Granacher, U., Muehlbauer, T., Zahner, L., Gollhofer, A., & Kressig, R. W. (2011). Comparison of Traditional and Recent Approaches in the Promotion of Balance and Strength in Older Adults. *Sports Medicine*, *41*(5), 377–400.
- Granacher, U., Zahner, L., & Gollhofer, A. (2008). Strength, power, and postural control in seniors: Considerations for functional adaptations and for fall prevention. *European Journal of Sport Science*, *8*(6), 325–340. <https://doi.org/10.1080/17461390802478066>
- Grissom, R. J., & Kim, J. J. (2012). *Effect sizes for research: Univariate and multivariate applications*. London: Routledge.
- Gruber, M., Taube, W., Gollhofer, A., Beck, S., Amtage, F., & Schubert, M. (2007). Training-specific adaptations of H- and stretch reflexes in human soleus muscle. *Journal of Motor Behavior*, *39*(1), 68–78. <https://doi.org/10.3200/JMBR.39.1.68-78>
- Gruber, M., & Gollhofer, A. (2004). Impact of sensorimotor training on the rate of force development and neural activation. *European Journal of Applied Physiology*, *92*(1-2), 98–105. <https://doi.org/10.1007/s00421-004-1080-y>
- Gschwind, Y. J., Kressig, R. W., Lacroix, A., Muehlbauer, T., Pfenninger, B., & Granacher, U. (2013). A best practice fall prevention exercise program to improve balance, strength / power, and psychosocial health in older adults: Study protocol for a randomized controlled trial. *BMC geriatrics*, *13*, 105. <https://doi.org/10.1186/1471-2318-13-105>

- Gschwind, Y. J., Wolf, I., Bridenbaugh, S. A., & Kressig, R. W. (2011). Basis for a Swiss perspective on fall prevention in vulnerable older people. *Swiss medical weekly*, *141*, w13305. <https://doi.org/10.4414/smw.2011.13305>
- Guermazi, M., Ghroubi, S., Kassis, M., Jaziri, O., Keskes, H., Kessomtini, W., . . . Elleuch, M.-H. (2006). [Validity and reliability of Spinal Mouse to assess lumbar flexion]. *Annales de readaptation et de medecine physique*, *49*(4), 172–177. <https://doi.org/10.1016/j.annrmp.2006.03.001>
- Gusi, N., Carmelo Adsuar, J., Corzo, H., Del Pozo-Cruz, B., Olivares, P. R., & Parraca, J. A. (2012). Balance training reduces fear of falling and improves dynamic balance and isometric strength in institutionalised older people: a randomised trial. *Journal of Physiotherapy*, *58*(2), 97–104. [https://doi.org/10.1016/s1836-9553\(12\)70089-9](https://doi.org/10.1016/s1836-9553(12)70089-9)
- Haekkinen, K., Kallinen, M., Izquierdo, M., Jokelainen, K., Lassila, H., Malkia, E., . . . Alen, M. (1998). Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *Journal of applied physiology (Bethesda, Md. : 1985)*, *84*(4), 1341–1349.
- Haekkinen, K., Kraemer, W. J., Newton, R. U., & Alen, M. (2001). Changes in electromyographic activity, muscle fibre and force production characteristics during heavy resistance/power strength training in middle-aged and older men and women. *Acta Physiologica Scandinavica*, *171*(1), 51–62. <https://doi.org/10.1046/j.1365-201X.2001.00781.x>
- Haekkinen, K. (2003). Ageing and neuromuscular adaptation to strength training. In P. V. Komi (Ed.), *An IOC Medical Commission publication: / in collabor. with the International Federation of Sports Medicine ; Vol. 3. Strength and power in sport* (2nd ed., pp. 409–425). Oxford: Blackwell Science.
- Haemaelaeninen, P., Suni, J., Pasanen, M., Malmberg, J., & Miilunpalo, S. (2006). Changes in physical performance among high-functioning older adults: A 6-year follow-up study. *European Journal of Ageing*, *3*(1), 3–14.
- Hedges, L. V., & Olkin, I. (1985). *Statistical methods for meta-analysis*. San Diego: Academic Press.
- Heinrich, S., Rapp, K., Rissmann, U., Becker, C., & Konig, H.-H. (2010). Cost of falls in old age: A systematic review. *Osteoporosis International*, *21*(6), 891–902. <https://doi.org/10.1007/s00198-009-1100-1>
- Helbostad, J. L., Sletvold, O., & Moe-Nilssen, R. (2004a). Effects of home exercises and group training on functional abilities in home-dwelling older persons with mobility and balance problems. A randomized study. *Ageing clinical and experimental research*, *16*(2), 113–121.
- Helbostad, J. L., Sletvold, O., & Moe-Nilssen, R. (2004b). Home training with and without additional group training in physically frail old people living at home: effect on health-related quality of life and ambulation. *Clinical rehabilitation*, *18*(5), 498–508.
- Henry, S. M., Fung, J., & Horak, F. B. (1998). EMG responses to maintain stance during multidirectional surface translations. *Journal of Neurophysiology*, *80*(4), 1939–1950.
- Hicks, G. E., Simonsick, E. M., Harris, T. B., Newman, A. B., Weiner, D. K., Nevitt, M. A., & Tyllavsky, F. A. (2005a). Cross-sectional associations between trunk muscle composition, back pain, and physical function in the health, aging and body composition study. *Journals of Gerontology Series a-Biological Sciences and Medical Sciences*, *60*(7), 882–887.

- Hicks, G. E., Simonsick, E. M., Harris, T. B., Newman, A. B., Weiner, D. K., Nevitt, M. A., & Tyllavsky, F. A. (2005b). Trunk muscle composition as a predictor of reduced functional capacity in the health, aging and body composition study: The moderating role of back pain. *The journals of gerontology. Series A, Biological sciences and medical sciences*, *60*(11), 1420–1424.
- Hill, K. D., Hunter, S. W., Batchelor, F. A., Cavalheri, V., & Burton, E. (2015). Individualized home-based exercise programs for older people to reduce falls and improve physical performance: A systematic review and meta-analysis. *Maturitas*, *82*(1), 72–84. <https://doi.org/10.1016/j.maturitas.2015.04.005>
- Hinman, M. (2002). Comparison of Two Short-term Balance Training Programs for Community-dwelling Older Adults. *Journal of Geriatric Physical Therapy*, *25*, 10–20.
- Hodges, P. W., & Richardson, C. A. (1997). Contraction of the abdominal muscles associated with movement of the lower limb. *Physical therapy*, *77*(2), 132–42; discussion 142–4.
- Hodges, P. W., & Richardson, C. A. (1999). Transversus abdominis and the superficial abdominal muscles are controlled independently in a postural task. *Neuroscience Letters*, *265*(2), 91–94.
- Horak, F. B. (2006). Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age and Ageing*, *35 Suppl 2*, ii7–ii11. <https://doi.org/10.1093/ageing/afl077>
- Hortobágyi, T., Lesinski, M., Gäbler, M., VanSwearingen, J., Malatesta, D., & Granacher, U. (2015). Effects of Three Types of Exercise Interventions on Healthy Old Adults' Gait Speed: A Systematic Review and Meta-Analysis. *Sports Medicine*, *45*(12), 1627–1643.
- Howe, T. E., Rochester, L., Neil, F., Skelton, D. A., & Ballinger, C. (2011). Exercise for improving balance in older people. *The Cochrane database of systematic reviews*, Cd004963. <https://doi.org/10.1002/14651858.CD004963.pub3>
- Hurvitz, E. A., Richardson, J. K., Werner, R. A., Ruhl, A. M., & Dixon, M. R. (2000). Unipedal stance testing as an indicator of fall risk among older outpatients. *Archives of Physical Medicine and Rehabilitation*, *81*, 587–591.
- Hytoenen, M., Pyykkoe, I., Aalto, H., & Starck, J. (1993). Postural control and age. *Acta Oto-Laryngologica*, *113*(2), 119–122.
- Imagama, S., Matsuyama, Y., Hasegawa, Y., Sakai, Y., Ito, Z., Ishiguro, N., & Hamajima, N. (2011). Back muscle strength and spinal mobility are predictors of quality of life in middle-aged and elderly males. *European Spine Journal*, *20*(6), 954–961. <https://doi.org/10.1007/s00586-010-1606-4>
- Isles, R. C., Choy, N. L. L., Steer, M., & Nitz, J. C. (2004). Normal values of balance tests in women aged 20–80. *Journal of the American Geriatrics Society*, *52*(8), 1367–1372. <https://doi.org/10.1111/j.1532-5415.2004.52370.x>
- Jacobs, J. M., & Love, S. (1985). Qualitative and quantitative morphology of human sural nerve at different ages. *Brain : a journal of neurology*, *108 (Pt 4)*, 897–924.
- Jacobs, J. V., & Horak, F. B. (2007). Cortical control of postural responses. *Journal of neural transmission (Vienna, Austria : 1996)*, *114*(10), 1339–1348. <https://doi.org/10.1007/s00702-007-0657-0>

- Jacobs, J. V., Horak, F. B., van Tran, K., & Nutt, J. G. (2006). An alternative clinical postural stability test for patients with Parkinson's disease. *Journal of neurology*, *253*(11), 1404–1413. <https://doi.org/10.1007/s00415-006-0224-x>
- Kadi, F., Charifi, N., Denis, C., & Lexell, J. (2004). Satellite cells and myonuclei in young and elderly women and men. *Muscle & Nerve*, *29*(1), 120–127. <https://doi.org/10.1002/mus.10510>
- Kallman, D. A., Plato, C. C., & Tobin, J. D. (1990). The role of muscle loss in the age-related decline of grip strength: cross-sectional and longitudinal perspectives. *Journal of gerontology*, *45*(3), M82-8.
- Kamen, G., & Knight, C. A. (2004). Training-related adaptations in motor unit discharge rate in young and older adults. *The journals of gerontology. Series A, Biological sciences and medical sciences*, *59*(12), 1334–1338.
- Karahan, A. Y., Tok, F., Taskin, H., Kucuksarac, S., Basaran, A., & Yildirim, P. (2015). Effects of Exergames on Balance, Functional Mobility, and Quality of Life of Geriatrics Versus Home Exercise Programme: Randomized Controlled Study. *Central European journal of public health*, *23 Suppl*, S14-8. <https://doi.org/10.21101/cejph.a4081>
- Kararizou, E., Manta, P., Kalfakis, N., & Vassilopoulos, D. (2005). Morphometric study of the human muscle spindle. *Analytical and quantitative cytology and histology*, *27*(1), 1–4.
- Kasukawa, Y., Miyakoshi, N., Hongo, M., Ishikawa, Y., Noguchi, H., Kamo, K., . . . Shimada, Y. (2010). Relationships between falls, spinal curvature, spinal mobility and back extensor strength in elderly people. *Journal of bone and mineral metabolism*, *28*(1), 82–87. <https://doi.org/10.1007/s00774-009-0107-1>
- Katzman, W., Cawthon, P., Hicks, G. E., Vittinghoff, E., Shepherd, J., Cauley, J. A., . . . Kado, D. M. (2012). Association of spinal muscle composition and prevalence of hyperkyphosis in healthy community-dwelling older men and women. *The journals of gerontology. Series A, Biological sciences and medical sciences*, *67*(2), 191–195. <https://doi.org/10.1093/gerona/67.2.191>
- Kennedy, K. M., & Raz, N. (2005). Age, sex and regional brain volumes predict perceptual-motor skill acquisition. *Cortex; a journal devoted to the study of the nervous system and behavior*, *41*(4), 560–569.
- Kerchner, G. A., Racine, C. A., Hale, S., Wilhelm, R., Laluz, V., Miller, B. L., & Kramer, J. H. (2012). Cognitive processing speed in older adults: Relationship with white matter integrity. *Plos One*, *7*(11), e50425. <https://doi.org/10.1371/journal.pone.0050425>
- Kibler, W. B., Press, J., & Sciascia, A. (2006). The role of core stability in athletic function. *Sports Medicine*, *36*(3), 189–198.
- Kido, T., Tabara, Y., Igase, M., Ochi, N., Uetani, E., Nagai, T., . . . Kohara, K. (2010). Postural instability is associated with brain atrophy and cognitive impairment in the elderly: The J-SHIP study. *Dementia and geriatric cognitive disorders*, *29*(5), 379–387. <https://doi.org/10.1159/000255106>
- Klitgaard, H., Zhou, M., Schiaffino, S., Betto, R., Salvati, G., & Saltin, B. (1990). Ageing alters the myosin heavy chain composition of single fibres from human skeletal muscle. *Acta Physiologica Scandinavica*, *140*(1), 55–62. <https://doi.org/10.1111/j.1748-1716.1990.tb08975.x>
- Kohler, A., Kressig, R. W., Schindler, C., & Granacher, U. (2012). [Adherence rate in intervention programs for the promotion of physical activity in older adults: a systematic literature review]. *Praxis (Bern 1994)*, *101*, 1535–1547. <https://doi.org/10.1024/1661-8157/a001129>

- Kojima, N., Kim, H., Saito, K., Yoshida, H., Yoshida, Y., Hirano, H., . . . Suzuki, T. (2014). Association of knee-extension strength with instrumental activities of daily living in community-dwelling older adults. *Geriatrics & Gerontology International*, *14*(3), 674–680. <https://doi.org/10.1111/ggi.12158>
- Korpelainen, R., Keinänen-Kiukaanniemi, S., Heikkinen, J., Väänänen, K., & Korpelainen, J. (2006). Effect of impact exercise on bone mineral density in elderly women with low BMD: A population-based randomized controlled 30-month intervention. *Osteoporosis International*, *17*(1), 109–118. <https://doi.org/10.1007/s00198-005-1924-2>
- Lacroix, A., Kressig, R. W., Muehlbauer, T., Gschwind, Y. J., Pfenninger, B., Bruegger, O., & Granacher, U. (2016). Effects of a Supervised versus an Unsupervised Combined Balance and Strength Training Program on Balance and Muscle Power in Healthy Older Adults: A Randomized Controlled Trial. *Gerontology*, *62*(3), 275–288. <https://doi.org/10.1159/000442087>
- Lacroix, A., Hortobágyi, T., Beurskens, R., & Granacher, U. (2017). Effects of Supervised vs. Unsupervised Training Programs on Balance and Muscle Strength in Older Adults: A Systematic Review and Meta-Analysis. *Sports medicine (Auckland, N.Z.)*, *47*(11), 2341–2361. <https://doi.org/10.1007/s40279-017-0747-6>
- Larsson, L., Grimby, G., & Karlsson, J. (1979). Muscle strength and speed of movement in relation to age and muscle morphology. *Journal of applied physiology: respiratory, environmental and exercise physiology*, *46*(3), 451–456.
- Larsson, L., Li, X., & Frontera, W. R. (1997). Effects of aging on shortening velocity and myosin isoform composition in single human skeletal muscle cells. *The American journal of physiology*, *272*(2 Pt 1), C638-49.
- Latham, N. K., Bennett, D. A., Stretton, C. M., & Anderson, C. S. (2004). Systematic review of progressive resistance strength training in older adults. *The journals of gerontology. Series A, Biological sciences and medical sciences*, *59*(1), 48–61.
- Lee, M. M., Song, C. H., Lee, K. J., Jung, S. W., Shin, D. C., & Shin, S. H. (2014). Concurrent Validity and Test-retest Reliability of the OPTOGait Photoelectric Cell System for the Assessment of Spatio-temporal Parameters of the Gait of Young Adults. *Journal of Physical Therapy Science*, *26*(1), 81–85. <https://doi.org/10.1589/jpts.26.81>
- Lencioni, T., Rabuffetti, M., Piscoquito, G., Pareyson, D., Aiello, A., Di Sipio, E., . . . Ferrarin, M. (2014). Postural stabilization and balance assessment in Charcot-Marie-Tooth 1A subjects. *Gait & Posture*, *40*(4), 481–486. <https://doi.org/10.1016/j.gaitpost.2014.07.006>
- Lesinski, M., Hortobágyi, T., Muehlbauer, T., Gollhofer, A., & Granacher, U. (2015a). Dose-response relationships of balance training in healthy young adults: A systematic review and meta-analysis. *Sports medicine (Auckland, N.Z.)*, *45*(4), 557–576. <https://doi.org/10.1007/s40279-014-0284-5>
- Lesinski, M., Hortobágyi, T., Muehlbauer, T., Gollhofer, A., & Granacher, U. (2015b). Effects of Balance Training on Balance Performance in Healthy Older Adults: A Systematic Review and Meta-analysis. *Sports Medicine*, *45*(12), 1721–1738. <https://doi.org/10.1007/s40279-015-0375-y>
- Lienhard, K., Schneider, D., & Maffioletti, N. A. (2013). Validity of the Optogait photoelectric system for the assessment of spatiotemporal gait parameters. *Medical engineering & physics*, *35*(4), 500–504. <https://doi.org/10.1016/j.medengphy.2012.06.015>

- Lin, M. R., Wolf, S. L., Hwang, H. F., Gong, S. Y., & Chen, C. Y. (2007). A randomized, controlled trial of fall prevention programs and quality of life in older fallers. *Journal of the American Geriatrics Society*, *55*(4), 499–506. <https://doi.org/10.1111/j.1532-5415.2007.01146.x>
- Lin, S.-I., & Woollacott, M. H. (2002). Postural muscle responses following changing balance threats in young, stable older, and unstable older adults. *Journal of Motor Behavior*, *34*(1), 37–44. <https://doi.org/10.1080/00222890209601929>
- Lindemann, U., Rupp, K., Mucbe, R., Nikolaus, T., & Becker, C. (2004). Improving balance by improving motor skills. *Zeitschrift für Gerontologie und Geriatrie*, *37*(1), 20–26. <https://doi.org/10.1007/s00391-004-0206-5>
- Liu, C. J., & Latham, N. K. (2009). Progressive resistance strength training for improving physical function in older adults. *The Cochrane database of systematic reviews*, Cd002759. <https://doi.org/10.1002/14651858.CD002759.pub2>
- Lopez, M. N., Charter, R. A., Mostafavi, B., Nibut, L. P., & Smith, W. E. (2005). Psychometric properties of the Folstein Mini-Mental State Examination. *Assessment*, *12*(2), 137–144. <https://doi.org/10.1177/1073191105275412>
- Lord, S. R., Castell, S., Corcoran, J., Dayhew, J., Matters, B., Shan, A., & Williams, P. (2003). The effect of group exercise on physical functioning and falls in frail older people living in retirement villages: a randomized, controlled trial. *Journal of the American Geriatrics Society*, *51*(12), 1685–1692.
- Lord, S. R., Sherrington, C., Cameron, I. D., & Close, J. C. T. (2011). Implementing falls prevention research into policy and practice in Australia: Past, present and future. *Journal of safety research*, *42*(6), 517–520. <https://doi.org/10.1016/j.jsr.2010.11.008>
- Lord, S. R., Sherrington, C., Menz, H. B., & Close, J. C. T. (2007). *Falls in older people: risk factors and strategies for prevention*. Cambridge: Cambridge University Press.
- Luff, A. R. (1998). Age-associated changes in the innervation of muscle fibers and changes in the mechanical properties of motor units. *Annals of the New York Academy of Sciences*, *854*, 92–101.
- Luukinen, H., Lehtola, S., Jokelainen, J., Vaananen-Sainio, R., Lotvonen, S., & Koistinen, P. (2007). Pragmatic exercise-oriented prevention of falls among the elderly: a population-based, randomized, controlled trial. *Preventive Medicine*, *44*(3), 265–271. <https://doi.org/10.1016/j.ypmed.2006.09.011>
- Lynch, N. A., Metter, E. J., Lindle, R. S., Fozard, J. L., Tobin, J. D., Roy, T. A., . . . Hurley, B. F. (1999). Muscle quality. I. Age-associated differences between arm and leg muscle groups. *Journal of applied physiology (Bethesda, Md. : 1985)*, *86*(1), 188–194.
- Macaluso, A., & Vito, G. de. (2004). Muscle strength, power and adaptations to resistance training in older people. *European Journal of Applied Physiology*, *91*(4), 450–472. <https://doi.org/10.1007/s00421-003-0991-3>
- Macaluso, A., Nimmo, M. A., Foster, J. E., Cockburn, M., McMillan, N. C., & Vito, G. de. (2002). Contractile muscle volume and agonist-antagonist coactivation account for differences in torque between young and older women. *Muscle & Nerve*, *25*(6), 858–863. <https://doi.org/10.1002/mus.10113>
- Magaziner, J., Hawkes, W., Hebel, J. R., Zimmerman, S. I., Fox, K. M., Dolan, M., . . . Kenzora, J. (2000). Recovery from hip fracture in eight areas of function. *The journals of gerontology. Series A, Biological sciences and medical sciences*, *55*(9), M498-507.



- Magaziner, J., Chiles, N., & Orwig, D. (2015). Recovery after Hip Fracture: Interventions and Their Timing to Address Deficits and Desired Outcomes--Evidence from the Baltimore Hip Studies. *Nestle Nutrition Institute workshop series*, 83, 71–81. <https://doi.org/10.1159/000382064>
- Maher, C. G., Sherrington, C., Herbert, R. D., Moseley, A. M., & Elkins, M. (2003). Reliability of the PEDro scale for rating quality of randomized controlled trials. *Physical therapy*, 83(8), 713–721.
- Malmberg, J. J., Miilunpalo, S. I., Vuori, I. M., Pasanen, M. E., Oja, P., & Haapanen-Niemi, N. A. (2002). A health-related fitness and functional performance test battery for middle-aged and older adults: Feasibility and health-related content validity. *Archives of Physical Medicine & Rehabilitation*, 83(5), 666–677.
- Mangione, K. K., Craik, R. L., Tomlinson, S. S., & Palombaro, K. M. (2005). Can elderly patients who have had a hip fracture perform moderate- to high-intensity exercise at home? *Physical therapy*, 85(8), 727–739.
- Manini, T. M., & Clark, B. C. (2012). Dynapenia and aging: an update. *The journals of gerontology. Series A, Biological sciences and medical sciences*, 67(1), 28–40. <https://doi.org/10.1093/gerona/glr010>
- Manos, P. J., & Wu, R. (1994). The ten point clock test: A quick screen and grading method for cognitive impairment in medical and surgical patients. *International journal of psychiatry in medicine*, 24(3), 229–244. <https://doi.org/10.2190/5A0F-936P-VG8N-0F5R>
- Martin, J. C., Farrar, R. P., Wagner, B. M., & Spirduso, W. W. (2000). Maximal power across the lifespan. *Journals of Gerontology Series a-Biological Sciences and Medical Sciences*, 55(6), M311-6.
- McNeil, C. J., Doherty, T. J., Stashuk, D. W., & Rice, C. L. (2005). Motor unit number estimates in the tibialis anterior muscle of young, old, and very old men. *Muscle & Nerve*, 31(4), 461–467. <https://doi.org/10.1002/mus.20276>
- McNeil, C. J., Vandervoort, A. A., & Rice, C. L. (2007). Peripheral impairments cause a progressive age-related loss of strength and velocity-dependent power in the dorsiflexors. *Journal of applied physiology (Bethesda, Md. : 1985)*, 102(5), 1962–1968. <https://doi.org/10.1152/jappphysiol.01166.2006>
- Mika, A., Fernhall, B., & Mika, P. (2009). Association between moderate physical activity, spinal motion and back muscle strength in postmenopausal women with and without osteoporosis. *Disability & Rehabilitation*, 31(9), 734–740. <https://doi.org/10.1080/09638280802308998>
- Mitchell, W. K., Williams, J., Atherton, P., Larvin, M., Lund, J., & Narici, M. (2012). Sarcopenia, dynapenia, and the impact of advancing age on human skeletal muscle size and strength; a quantitative review. *Frontiers in physiology*, 3, 260. <https://doi.org/10.3389/fphys.2012.00260>
- Miyakoshi, N., Hongo, M., Maekawa, S., Ishikawa, Y., Shimada, Y., & Itoi, E. (2007). Back extensor strength and lumbar spinal mobility are predictors of quality of life in patients with postmenopausal osteoporosis. *Osteoporosis International*, 18(10), 1397–1403. <https://doi.org/10.1007/s00198-007-0383-3>
- Miyakoshi, N., Hongo, M., Maekawa, S., Ishikawa, Y., Shimada, Y., Okada, K., & Itoi, E. (2005). Factors related to spinal mobility in patients with postmenopausal osteoporosis. *Osteoporosis International*, 16(12), 1871–1874. <https://doi.org/10.1007/s00198-005-1953-x>
- Morse, C. I., Thom, J. M., Mian, O. S., Birch, K. M., & Narici, M. V. (2007). Gastrocnemius specific force is increased in elderly males following a 12-month physical training programme. *European Journal of Applied Physiology*, 100(5), 563–570. <https://doi.org/10.1007/s00421-006-0246-1>

- Muehlbauer, T., Besemer, C., Wehrle, A., Gollhofer, A., & Granacher, U. (2012). Relationship between strength, power and balance performance in seniors. *Gerontology*, *58*(6), 504–512. <https://doi.org/10.1159/000341614>
- Muehlbauer, T., Gollhofer, A., & Granacher, U. (2012). Relationship between measures of balance and strength in middle-aged adults. *Journal of Strength and Conditioning Research*, *26*(9), 2401–2407. <https://doi.org/10.1519/JSC.0b013e31823f8c41>
- Mueller, O., Guenther, M., Krauss, I., & Horstmann, T. (2004). [Physical characterization of the therapeutic device Posturomed as a measuring device-presentation of a procedure to characterize balancing ability]. *Biomedizinische Technik. Biomedical engineering*, *49*(3), 56–60. <https://doi.org/10.1515/BMT.2004.011>
- Mynark, R. G., & Koceja, D. M. (2002). Down training of the elderly soleus H reflex with the use of a spinally induced balance perturbation. *Journal of applied physiology (Bethesda, Md. : 1985)*, *93*(1), 127–133. <https://doi.org/10.1152/jappphysiol.00007.2001>
- Narici, M. V., Bordini, M., & Cerretelli, P. (1991). Effect of aging on human adductor pollicis muscle function. *Journal of applied physiology (Bethesda, Md. : 1985)*, *71*(4), 1277–1281.
- Narici, M. V., Maganaris, C. N., Reeves, N. D., & Capodaglio, P. (2003). Effect of aging on human muscle architecture. *Journal of applied physiology (Bethesda, Md. : 1985)*, *95*(6), 2229–2234. <https://doi.org/10.1152/jappphysiol.00433.2003>
- Narici, M. V., & Maganaris, C. N. (2007). Plasticity of the muscle-tendon complex with disuse and aging. *Exercise and Sport Sciences Reviews*, *35*(3), 126–134. <https://doi.org/10.1097/jes.0b013e3180a030ec>
- Nevitt, M. C., Cummings, S. R., & Hudes, E. S. (1991). Risk factors for injurious falls: A prospective study. *Journal of gerontology*, *46*(5), M164-70.
- Newton, R. A. (2001). Validity of the multi-directional reach test: A practical measure for limits of stability in older adults. *Journals of Gerontology Series a-Biological Sciences and Medical Sciences*, *56*(4), M248-52.
- Nicola, F., & Catherine, S. (2011). Dose-response relationship of resistance training in older adults: a meta-analysis. *British journal of sports medicine*, *45*(3), 233–234. <https://doi.org/10.1136/bjism.2010.083246>
- Oberg, T., Karsznia, A., & Oberg, K. (1993). Basic gait parameters: Reference data for normal subjects, 10-79 years of age. *Journal of Rehabilitation Research & Development*, *30*(2), 210–223.
- Opdenacker, J., Delecluse, C., & Boen, F. (2011). A 2-year follow-up of a lifestyle physical activity versus a structured exercise intervention in older adults. *Journal of the American Geriatrics Society*, *59*, 1602–1611. <https://doi.org/10.1111/j.1532-5415.2011.03551.x>
- Orr, R. (2010). Contribution of muscle weakness to postural instability in the elderly. A systematic review. *European journal of physical and rehabilitation medicine*, *46*(2), 183–220.
- Orr, R., Raymond, J., & Fiatarone Singh, M. (2008). Efficacy of progressive resistance training on balance performance in older adults: A systematic review of randomized controlled trials. *Sports medicine (Auckland, N.Z.)*, *38*(4), 317–343.
- Oswald, W. D., Gunzelmann, T., Rupprecht, R., & Hagen, B. (2006). Differential effects of single versus combined cognitive and physical training with older adults: the SimA study in a 5-year perspective. *European Journal of Ageing*, *3*(4), 179–192.

- Paalanne, N. P., Korpelainen, R., Taimela, S. P., Remes, J., Salakka, M., & Karppinen, J. I. (2009). Reproducibility and reference values of inclinometric balance and isometric trunk muscle strength measurements in Finnish young adults. *The Journal of Strength & Conditioning Research*, *23*(5), 1618–1626.
- Papegaaij, S., Taube, W., Baudry, S., Otten, E., & Hortobágyi, T. (2014). Aging causes a reorganization of cortical and spinal control of posture. *Frontiers in aging neuroscience*, *6*, 28. <https://doi.org/10.3389/fnagi.2014.00028>
- Park, H., Kim, K. J., Komatsu, T., Park, S. K., & Mutoh, Y. (2008). Effect of combined exercise training on bone, body balance, and gait ability: a randomized controlled study in community-dwelling elderly women. *Journal of bone and mineral metabolism*, *26*(3), 254–259. <https://doi.org/10.1007/s00774-007-0819-z>
- Peel, N. M., Kassulke, D. J., & McClure, R. J. (2002). Population based study of hospitalised fall related injuries in older people. *Injury Prevention*, *8*(4), 280–283.
- Perera, S., Mody, S. H., Woodman, R. C., & Studenski, S. A. (2006). Meaningful change and responsiveness in common physical performance measures in older adults. *Journal of the American Geriatrics Society*, *54*(5), 743–749. <https://doi.org/10.1111/j.1532-5415.2006.00701.x>
- Pfeifer, M., Begerow, B., Minne, H. W., Schlotthauer, T., Pospeschill, M., Scholz, M., . . . Pollähne, W. (2001). Vitamin D status, trunk muscle strength, body sway, falls, and fractures among 237 postmenopausal women with osteoporosis. *Experimental and clinical endocrinology & diabetes*, *109*(2), 87–92. <https://doi.org/10.1055/s-2001-14831>
- Pildal, J., Hróbjartsson, A., Jørgensen, K. J., Hilden, J., Altman, D. G., & Gøtzsche, P. C. (2007). Impact of allocation concealment on conclusions drawn from meta-analyses of randomized trials. *International journal of epidemiology*, *36*(4), 847–857. <https://doi.org/10.1093/ije/dym087>
- Podsiadlo, D., & Richardson, S. (1991). The timed "Up & Go": A test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society*, *39*(2), 142–148.
- Poetzsch, O., & Roeßger, F. (2015). *Bevölkerung Deutschlands bis 2060: 13. koordinierte Bevölkerungsvoraberechnung*. Statistisches Bundesamt. Wiesbaden.
- Rantanen, T., Era, P., & Heikkinen, E. (1997). Physical activity and the changes in maximal isometric strength in men and women from the age of 75 to 80 years. *Journal of the American Geriatrics Society*, *45*(12), 1439–1445.
- Rantanen, T., Avlund, K., Suominen, H., Schroll, M., Frandin, K., & Pertti, E. (2002). Muscle strength as a predictor of onset of ADL dependence in people aged 75 years. *Aging Clinical and Experimental Research*, *14*(3 Suppl), 10–15.
- Rapp, K., Freiberger, E., Todd, C., Klenk, J., Becker, C., Denking, M., . . . Fuchs, J. (2014). Fall incidence in Germany: Results of two population-based studies, and comparison of retrospective and prospective falls data collection methods. *BMC geriatrics*, *14*, 105. <https://doi.org/10.1186/1471-2318-14-105>
- Reeves, N. D., Narici, M. V., & Maganaris, C. N. (2003). Strength training alters the viscoelastic properties of tendons in elderly humans. *Muscle & Nerve*, *28*(1), 74–81. <https://doi.org/10.1002/mus.10392>

- Reeves, N. D., Narici, M. V., & Maganaris, C. N. (2004). In vivo human muscle structure and function: adaptations to resistance training in old age. *Experimental Physiology*, *89*(6), 675–689. <https://doi.org/10.1113/expphysiol.2004.027797>
- Robertson, M. C., Devlin, N., Gardner, M. M., & Campbell, A. J. (2001). Effectiveness and economic evaluation of a nurse delivered home exercise programme to prevent falls. 1: Randomised controlled trial. *BMJ*, *322*(7288), 697–701.
- Rosano, C., Sigurdsson, S., Siggeirsdottir, K., Phillips, C. L., Garcia, M., Jonsson, P. V., . . . Launer, L. J. (2010). Magnetization transfer imaging, white matter hyperintensities, brain atrophy and slower gait in older men and women. *Neurobiology of Aging*, *31*(7), 1197–1204. <https://doi.org/10.1016/j.neurobiolaging.2008.08.004>
- Roubenoff, R., & Hughes, V. A. (2000). Sarcopenia: current concepts. *The journals of gerontology. Series A, Biological sciences and medical sciences*, *55*(12), M716-24.
- Rubenstein, L. Z. (2006). Falls in older people: epidemiology, risk factors and strategies for prevention. *Age and Ageing*, *35* Suppl 2, ii37-ii41. <https://doi.org/10.1093/ageing/afl084>
- Rubenstein, L. Z., & Josephson, K. R. (2002). The epidemiology of falls and syncope. *Clinics in geriatric medicine*, *18*(2), 141–158.
- Ryberg, C., Rostrup, E., Paulson, O. B., Barkhof, F., Scheltens, P., van Straaten, E. C. W., . . . Waldemar, G. (2011). Corpus callosum atrophy as a predictor of age-related cognitive and motor impairment: A 3-year follow-up of the LADIS study cohort. *Journal of the neurological sciences*, *307*(1-2), 100–105. <https://doi.org/10.1016/j.jns.2011.05.002>
- Sakai, M., Shiba, Y., Sato, H., & Takahira, N. (2008). Motor adaptation during slip-perturbed gait in older adults. *Journal of Physical Therapy Science*, *20*(2), 109–115.
- Sakari-Rantala, R., Era, P., Rantanen, T., & Heikkinen, E. (1998). Associations of sensory-motor functions with poor mobility in 75- and 80-year-old people. *Scandinavian Journal of Rehabilitation Medicine*, *30*(2), 121–127.
- Schättin, A., Arner, R., Gennaro, F., & Bruin, E. D. de. (2016). Adaptations of Prefrontal Brain Activity, Executive Functions, and Gait in Healthy Elderly Following Exergame and Balance Training: A Randomized-Controlled Study. *Frontiers in aging neuroscience*, *8*, 278. <https://doi.org/10.3389/fnagi.2016.00278>
- Schenkman, M., Shipp, K. M., Chandler, J., Studenski, S. A., & Kuchibhatla, M. (1996). Relationships between mobility of axial structures and physical performance. *Physical therapy*, *76*(3), 276–285.
- Schott, N., & Kurz, A.-K. (2008). Falls in older adults: Risk factors assessment prevention. A review. *Zeitschrift für Sportpsychologie*, *15*(2), 45–62.
- Seco, J., Abecia, L. C., Echevarria, E., Barbero, I., Torres-Unda, J., Rodriguez, V., & Calvo, J. I. (2013). A long-term physical activity training program increases strength and flexibility, and improves balance in older adults. *Rehabilitation nursing*, *38*(1), 37–47. <https://doi.org/10.1002/rmj.64>
- Seichert, N., Baumann, M., Senn, E., & Zuckriegel, H. (1994). [The “back mouse”-an analog-digital measuring device to record the sagittal outline of the back]. *Physikalische Medizin, Rehabilitationsmedizin, Kurortmedizin*, *4*(2), 35–43.

- Sherrington, C., Michaleff, Z. A., Fairhall, N., Paul, S. S., Tiedemann, A., Whitney, J., . . . Lord, S. R. (2016). Exercise to prevent falls in older adults: an updated systematic review and meta-analysis. *British journal of sports medicine*. Advance online publication. <https://doi.org/10.1136/bjsports-2016-096547>.
- Shier, V., Trieu, E., & Ganz, D. A. (2016). Implementing exercise programs to prevent falls: Systematic descriptive review. *Injury epidemiology*, 3, 16. <https://doi.org/10.1186/s40621-016-0081-8>
- Shulman, K. I. (2000). Clock-drawing: Is it the ideal cognitive screening test? *International Journal of Geriatric Psychiatry*, 15(6), 548–561.
- Shumway-Cook, A., Baldwin, M., Polissar, N. L., & Gruber, W. (1997). Predicting the probability for falls in community-dwelling older adults. *Physical therapy*, 77(8), 812–819.
- Shumway-Cook, A., & Woollacott, M. H. (2017). *Motor control: translating research into clinical practice* (5th ed.). Philadelphia: Lippincott Williams & Wilkins.
- Shumway-Cook, A., Brauer, S., & Woollacott, M. (2000). Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Physical therapy*, 80(9), 896–903.
- Silsupadol, P., Shumway-Cook, A., Lugade, V., van Donkelaar, P., Chou, L. S., Mayr, U., & Woollacott, M. H. (2009). Effects of single-task versus dual-task training on balance performance in older adults: a double-blind, randomized controlled trial. *Archives of Physical Medicine and Rehabilitation*, 90(3), 381–387. <https://doi.org/10.1016/j.apmr.2008.09.559>
- Simek, E. M., McPhate, L., Hill, K. D., Finch, C. F., Day, L., & Haines, T. P. (2015). What Are the Characteristics of Home Exercise Programs That Older Adults Prefer? A Cross-Sectional Study. *American journal of physical medicine & rehabilitation*, 94(7), 508–521. <https://doi.org/10.1097/phm.0000000000000275>
- Sinaki, M., Nwaogwugwu, N. C., Phillips, B. E., & Mokri, M. P. (2001). Effect of gender, age, and anthropometry on axial and appendicular muscle strength. *American journal of physical medicine & rehabilitation*, 80(5), 330–338.
- Skelton, D. A., Greig, C. A., Davies, J. M., & Young, A. (1994). Strength, power and related functional ability of healthy people aged 65-89 years. *Age and Ageing*, 23(5), 371–377.
- Skevington, S. M., Lotfy, M., & O'Connell, K. A. (2004). The World Health Organization's WHOQOL-BREF quality of life assessment: Psychometric properties and results of the international field trial. A report from the WHOQOL group. *Quality of Life Research*, 13(2), 299–310. <https://doi.org/10.1023/B:QURE.0000018486.91360.00>
- Smulders, E., Weerdesteijn, V., Groen, B. E., Duysens, J., Eijsbouts, A., Laan, R., & van Lankveld, W. (2010). Efficacy of a short multidisciplinary falls prevention program for elderly persons with osteoporosis and a fall history: A randomized controlled trial. *Archives of Physical Medicine and Rehabilitation*, 91(11), 1705–1711. <https://doi.org/10.1016/j.apmr.2010.08.004>
- Springer, B. A., Marin, R., Cyhan, T., Roberts, H., & Gill, N. W. (2007). Normative values for the unipedal stance test with eyes open and closed. *Journal of geriatric physical therapy*, 30(1), 8–15.
- Sridharan, A., Willette, A. A., Bendlin, B. B., Alexander, A. L., Coe, C. L., Voytko, M. L., . . . Johnson, S. C. (2012). Brain volumetric and microstructural correlates of executive and motor performance in aged rhesus monkeys. *Frontiers in aging neuroscience*, 4, 31. <https://doi.org/10.3389/fnagi.2012.00031>

- Stathi, A., McKenna, J., & Fox, K. R. (2010). Processes associated with participation and adherence to a 12-month exercise programme for adults aged 70 and older. *Journal of Health Psychology, 15*(6), 838–847. <https://doi.org/10.1177/1359105309357090>
- Steffen, T. M., Hacker, T. A., & Mollinger, L. (2002). Age- and gender-related test performance in community-dwelling elderly people: Six-Minute Walk Test, Berg Balance Scale, Timed Up & Go Test, and gait speeds. *Physical therapy, 82*(2), 128–137.
- Steib, S., Schoene, D., & Pfeifer, K. (2010). Dose-response relationship of resistance training in older adults: a meta-analysis. *Medicine and Science in Sports and Exercise, 42*(5), 902–914. <https://doi.org/10.1249/MSS.0b013e3181c34465>
- Stevens, J. A., Corso, P. S., Finkelstein, E. A., & Miller, T. R. (2006). The costs of fatal and non-fatal falls among older adults. *Injury Prevention, 12*(5), 290–295. <https://doi.org/10.1136/ip.2005.011015>
- Suetta, C., Aagaard, P., Rosted, A., Jakobsen, A. K., Duss, B., Kjaer, M., & Magnusson, S. P. (2004). Training-induced changes in muscle CSA, muscle strength, EMG, and rate of force development in elderly subjects after long-term unilateral disuse. *Journal of Applied Physiology, 97*(5), 1954–1961. <https://doi.org/10.1152/jappphysiol.01307.2003>
- Suri, P., Kiely, D. K., Leveille, S. G., Frontera, W. R., & Bean, J. F. (2009). Trunk muscle attributes are associated with balance and mobility in older adults: A pilot study. *PM & R, 1*(10), 916–924. <https://doi.org/10.1016/j.pmrj.2009.09.009>
- Suzuki, T., Kim, H., Yoshida, H., & Ishizaki, T. (2004). Randomized controlled trial of exercise intervention for the prevention of falls in community-dwelling elderly Japanese women. *Journal of bone and mineral metabolism, 22*, 602–611. <https://doi.org/10.1007/s00774-004-0530-2>
- Tang, P. F., & Woollacott, M. H. (1998). Inefficient postural responses to unexpected slips during walking in older adults. *Journals of Gerontology Series a-Biological Sciences and Medical Sciences, 53*(6), M471-80.
- Taube, W., Gruber, M., Beck, S., Faist, M., Gollhofer, A., & Schubert, M. (2007). Cortical and spinal adaptations induced by balance training: Correlation between stance stability and corticospinal activation. *Acta Physiologica, 189*(4), 347–358. <https://doi.org/10.1111/j.1748-1716.2007.01665.x>
- Taube, W., Gruber, M., & Gollhofer, A. (2008). Spinal and supraspinal adaptations associated with balance training and their functional relevance. *Acta Physiologica, 193*(2), 101–116.
- Taube, W., Kullmann, N., Leukel, C., Kurz, O., Amtage, F., & Gollhofer, A. (2007). Differential reflex adaptations following sensorimotor and strength training in young elite athletes. *International Journal of Sports Medicine, 28*(12), 999–1005. <https://doi.org/10.1055/s-2007-964996>
- Taylor, R. S., Dalal, H., Jolly, K., Zawada, A., Dean, S. G., Cowie, A., & Norton, R. J. (2015). Home-based versus centre-based cardiac rehabilitation. *The Cochrane Library, 8*, CD007130.
- Terao, S., Sobue, G., Hashizume, Y., Li, M., Inagaki, T., & Mitsuma, T. (1996). Age-related changes in human spinal ventral horn cells with special reference to the loss of small neurons in the intermediate zone: A quantitative analysis. *Acta neuropathologica, 92*(2), 109–114.

- Thalmann, B., Spiegel, R., Stähelin, H. B., Brubacher, D., Ermini-Fünfschilling, D., Bläsi, S., & Monsch, A. U. (2002). Dementia screening in general practice: Optimised scoring for the clock drawing test. *Brain Aging*, 2(2), 36–43.
- Thiebaud, R. S., Funk, M. D., & Abe, T. (2014). Home-based resistance training for older adults: a systematic review. *Geriatrics & Gerontology International*, 14(4), 750–757. <https://doi.org/10.1111/ggi.12326>
- Thom, J. M., Morse, C. I., Birch, K. M., & Narici, M. V. (2007). Influence of muscle architecture on the torque and power-velocity characteristics of young and elderly men. *European Journal of Applied Physiology*, 100(5), 613–619. <https://doi.org/10.1007/s00421-007-0481-0>
- Tiedemann, A., Shimada, H., Sherrington, C., Murray, S., & Lord, S. (2008). The comparative ability of eight functional mobility tests for predicting falls in community-dwelling older people. *Age and Ageing*, 37(4), 430–435. <https://doi.org/10.1093/ageing/afn100>
- Tinetti, M. E. (2003). Clinical practice. Preventing falls in elderly persons. *The New England journal of medicine*, 348(1), 42–49. <https://doi.org/10.1056/NEJMcp020719>
- Tinetti, M. E., Doucette, J., Claus, E., & Marottoli, R. (1995). Risk factors for serious injury during falls by older persons in the community. *Journal of the American Geriatrics Society*, 43(11), 1214–1221.
- Tinetti, M. E., Speechley, M., & Ginter, S. F. (1988). Risk factors for falls among elderly persons living in the community. *The New England journal of medicine*, 319(26), 1701–1707. <https://doi.org/10.1056/NEJM198812293192604>
- Tomlinson, B. E., & Irving, D. (1977). The numbers of limb motor neurons in the human lumbosacral cord throughout life. *Journal of the neurological sciences*, 34(2), 213–219.
- Tuunainen, E., Jantti, P., Pyykko, I., Rasku, J., Moisio-Vilenius, P., Makinen, E., & Toppila, E. (2013). Intervention to prevent falls in elderly adults living in a residential home. *Journal of the American Geriatrics Society*, 61(8), 1426–1427. <https://doi.org/10.1111/jgs.12395>
- United Nations. (2015). *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*. Working Paper No. ESA/P/WP.241.
- Valkovic, P., Brozová, H., Bötzel, K., Růzicka, E., & Benetin, J. (2008). Push-and-release test predicts Parkinson fallers and nonfallers better than the pull test: Comparison in OFF and ON medication states. *Movement Disorders*, 23(10), 1453–1457. <https://doi.org/10.1002/mds.22131>
- van Kan, G. A., Rolland, Y., Andrieu, S., Bauer, J., Beauchet, O., Bonnefoy, M., . . . Inzitari, M. (2009). Gait speed at usual pace as a predictor of adverse outcomes in community-dwelling older people an International Academy on Nutrition and Aging (IANA) Task Force. *The journal of nutrition, health & aging*, 13(10), 881–889.
- van Mechelen, W., Hlobil, H., & Kemper, H. C. (1992). Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Medicine*, 14(2), 82–99.
- van Roie, E., Delecluse, C., Opdenacker, J., Bock, K. de, Kennis, E., & Boen, F. (2010). Effectiveness of a Lifestyle Physical Activity Versus a Structured Exercise Intervention in Older Adults. *Journal of Aging and Physical Activity*, 18(3), 335–352.

- Viitasalo, J. T., Era, P., Leskinen, A.-L., & Heikkinen, E. (1985). Muscular strength profiles and anthropometry in random samples of men aged 31-35, 51-55 and 71-75 years. *Ergonomics*, *28*(11), 1563–1574.
- Watson, S. L., Weeks, B. K., Weis, L. J., Horan, S. A., & Beck, B. R. (2015). Heavy resistance training is safe and improves bone, function, and stature in postmenopausal women with low to very low bone mass: novel early findings from the LIFTMOR trial. *Osteoporosis International*, *26*(12), 2889–2894. <https://doi.org/10.1007/s00198-015-3263-2>
- Wechsler, D. (1997). *The Wechsler adult intelligence scale-III*. San Antonio, TX: Psychological Corporation.
- Wolfson, L., Judge, J., Whipple, R., & King, M. (1995). Strength is a major factor in balance, gait, and the occurrence of falls. *The journals of gerontology. Series A, Biological sciences and medical sciences*, *50 Spec No*, 64–67.
- Woollacott, M. H., & Tang, P. F. (1997). Balance control during walking in the older adult: Research and its implications. *Physical therapy*, *77*(6), 646–660.
- Wu, G., Keyes, L., Callas, P., Ren, X., & Bookchin, B. (2010). Comparison of telecommunication, community, and home-based Tai Chi exercise programs on compliance and effectiveness in elders at risk for falls. *Archives of Physical Medicine and Rehabilitation*, *91*(6), 849–856. <https://doi.org/10.1016/j.apmr.2010.01.024>
- Wu, G., Zhao, F., Zhou, X., & Wei, L. (2002). Improvement of isokinetic knee extensor strength and reduction of postural sway in the elderly from long-term Tai Chi exercise. *Archives of Physical Medicine and Rehabilitation*, *83*(10), 1364–1369.
- Yardley, L., Beyer, N., Hauer, K., Kempen, G., Piot-Ziegler, C., & Todd, C. (2005). Development and initial validation of the Falls Efficacy Scale-International (FES-I). *Age and Ageing*, *34*(6), 614–619. <https://doi.org/10.1093/ageing/afi196>
- Zhuang, J., Huang, L., Wu, Y., & Zhang, Y. (2014). The effectiveness of a combined exercise intervention on physical fitness factors related to falls in community-dwelling older adults. *Clinical Interventions in Aging*, *9*, 131–140. <https://doi.org/10.2147/cia.s56682>



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I deeply thank my family for their emotional and financial support during the past years. My parents Elke and Arno Lacroix always approved and supported my ideas since the beginning of my studies. Lastly and most importantly, I thank Stefanie, my wife and companion for more than thirteen years, and Marlon, my lovely son, for their patience, unconditional support, and love.

## Authors' contribution

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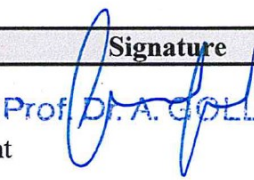

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The signed confirmations can be found on the following pages.

## Confirmation Albert Gollhofer and Katrin Roettger

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## Confirmation Barbara Pfenninger

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## Confirmation Othmar Bruegger

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## Confirmation Rainer Beurskens

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## Confirmation Reto W. Kressig

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## Confirmation Thomas Muehlbauer

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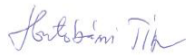
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## Confirmation Tibor Hortobágyi

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## Confirmation Urs Granacher

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## Confirmation Yves J. Gschwind

### Authors' contribution

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## Confirmation André Lacroix

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## Publication I

### RELATIONSHIPS BETWEEN TRUNK MUSCLE STRENGTH, SPINAL MOBILITY, AND BALANCE PERFORMANCE IN OLDER ADULTS

Urs Granacher<sup>1</sup>, André Lacroix<sup>1</sup>, Katrin Roettger<sup>2</sup>, Albert Gollhofer<sup>2</sup> & Thomas Muehlbauer<sup>1</sup>

<sup>1</sup> Division of Training and Movement Science, University of Potsdam, Potsdam, Germany

<sup>2</sup> Institute of Sport and Sport Science, Albert-Ludwigs-University Freiburg, Freiburg, Germany

## Reference

Granacher, U., Lacroix, A., Roettger, K., Gollhofer, A., & Muehlbauer, T. (2014). Relationships between trunk muscle strength, spinal mobility, and balance performance in older adults. *Journal of Aging & Physical Activity*, 22(4), 490–498. doi: 10.1123/japa.2013-0108

The final publication is available at  
<http://journals.humankinetics.com/doi/abs/10.1123/japa.2013-0108>



**Abstract**

This study investigated associations between variables of trunk muscle strength (TMS), spinal mobility, and balance in seniors. Thirty-four seniors (sex: 18 female, 16 male, age:  $70 \pm 4$  years, activity level:  $13 \pm 7$  hr/week) were tested for maximal isometric strength (MIS) of the trunk flexors/extensors, lateral flexors, rotators, spinal mobility (i.e., sagittal and coronal plane), and static/dynamic steady-state, reactive, and proactive balance. Significant correlations were detected between all measures of TMS and static steady-state balance ( $r = 0.43-0.57$ ,  $p < 0.05$ ). Significant correlations were observed between specific measures of TMS (i.e., MIS in sagittal plane, MIS in trunk rotators) and dynamic steady-state balance ( $r = 0.42-0.55$ ,  $p < 0.05$ ). No significant correlations were found between all variables of TMS and reactive and proactive balance and between all variables of spinal mobility and balance. Regression analyses revealed that TMS explains between 1-33 % of total variance of the respective balance parameters. Findings indicate that TMS is related to measures of static/dynamic steady-state balance which may imply that TMS promoting exercises should be integrated in strength training for seniors.

**Keywords:** elderly; core; gait; postural balance; force; physical performance

## Introduction

The aging process is frequently characterized by a flexed (i.e., hyperkyphotic) posture (Balzini et al., 2003) and/or an impaired spinal mobility (Haemaelaenen, Suni, Pasanen, Malmberg, & Miilunpalo, 2006) resulting in diminished mobility in older adults (Ryan & Fried, 1997). This is, amongst others, caused by an age-related loss in trunk muscle strength (TMS) and mass. In fact, older men aged 71-75 years showed 35 % and 45 % lower maximal isometric trunk flexion and extension strength compared to a group of 31-35 year old men (Viitasalo, Era, Leskinen, & Heikkinen, 1985). Further, Abe et al. (2011) observed a gradual decrease in trunk muscle mass in men and women aged 20 to 95 years. In addition, Kasukawa et al. (2010) were able to show that back extensor strength, lumbar kyphosis, mobility of the lumbar spine, and mobility of spinal inclination were significantly associated with presence/absence of falls in elderly individuals aged 60-97 years. Based on the findings of these cross-sectional studies, it appears that TMS is associated with spinal kyphosis as well as spinal mobility and may thus modulate balance, mobility, and falls.

However, findings from a recently published systematic literature review on potential associations between variables of TMS, trunk muscle composition, balance, functional performance, and falls in older adults revealed only small to medium correlations (Granacher, Gollhofer, Hortobagyi, Kressig, & Muehlbauer, 2013). It should be noted though that the authors classified their results as preliminary given that only six studies were found and included in their review. Of the six studies, three studies investigated older adults who suffered from chronic diseases (e.g., osteoporosis, back pain) (Hicks et al., 2005a, 2005b; Pfeifer et al., 2001). Two studies examined mobility impaired seniors (e.g., had a history of falls) (Kasukawa et al., 2010; Suri, Kiely, Leveille, Frontera, & Bean, 2009). In addition, the applied testing methodology varied largely between the six studies. For instance, TMS was assessed using repetition maximum tests on customized trunk resistance training machines (Suri et al., 2009), instrumented apparatus (e.g., isokinetic dynamometer, strain/pressure/force-gauge dynamometer/manual tester) (Kasukawa et al., 2010; Pfeifer et al., 2001), and clinical tests (e.g., McGill's trunk extensor/flexor endurance test) (Suri et al., 2009). Two studies investigated trunk muscle composition (i.e., muscle area/attenuation) using computerized tomography (Hicks et al., 2005a, 2005b). Tests of balance and functional performance comprised static balance tests (e.g., postural sway during one-legged stance) (Kasukawa et al., 2010; Pfeifer et al., 2001; Suri et al., 2009), balance test batteries (e.g., Berg balance scale) (Suri et al., 2009), and physical performance batteries (e.g., Health ABC physical performance battery) (Hicks et

al., 2005a, 2005b). Two studies determined rate of falls retrospectively (Kasukawa et al., 2010; Pfeifer et al., 2001). Moreover, there was substantial variability in test modality (e.g., number of practice and/or test trials). Thus, the included studies were heterogeneous in terms of the investigated subjects and the applied testing methodology. Based on these preliminary findings in the literature, additional well-designed correlative analyses are needed that investigate the relationship between measures of TMS, balance and functional performance in old age. Further, no study has been conducted yet that investigated associations between spinal mobility and balance as well as functional performance in seniors. Knowledge regarding potential relationships between variables of TMS, spinal mobility and balance as well as functional performance may help to develop specifically tailored intervention programs that have the potential to improve balance and functional performance in older adults by ultimately reducing the number of falls.

Thus, the aim of this study was to investigate associations between measures of TMS, spinal mobility as well as steady-state (i.e., maintaining a steady position in sitting, standing, and walking), reactive (i.e., compensation of a disturbance), and proactive (i.e., anticipation of a predicted disturbance) balance in older adults. It is hypothesized that both TMS and spinal mobility are related to measures of steady-state, reactive, and proactive balance.

## **Methods**

### *Participants*

Thirty-four community-dwelling older adults between the ages of 63 to 80 years gave written informed consent to participate in the study after experimental procedures were explained. Study participants were recruited by publishing advertisements in local newspapers. Participants' characteristics are presented in Table 1. A physiotherapist examined all participants before the start of the study. None had any history of musculoskeletal, neurological or orthopedic disorders that might have affected their ability to perform TMS, spinal mobility, and balance tests. The participants had no prior experience with the applied tests and they were capable of walking independently without any assistive device. Further, only cognitively healthy older adults were eligible to participate in the study [i.e., non-pathological rating in the Clock Drawing Test (CDT), Mini Mental State Examination Score (MMSE) of  $\geq 24$ ]. Local ethical permission was given and all experiments were conducted according to the latest version of the declaration of Helsinki.

**Table 1:** Characteristics of the study sample ( $N = 34$ ).

Characteristic	Mean ( <i>SD</i> ) or N (%)	Range
Sex (females)	18 (53 %)	n/a
Age (years)	70.4 (4.4)	63.0-81.0
Height (cm)	167.6 (7.4)	156.0-191.0
Mass (kg)	71.9 (13.1)	46.0-105.0
BMI ( $\text{m}/\text{kg}^2$ )	25.5 (3.7)	18.0-35.0
CDT	all participants were classified as non-pathological	
MMSE	28.1 (1.3)	26.0-30.0
Physical activity (hr/week)	13.0 (7.3)	1.0-17.0
Trunk muscle strength		
MIS in CRP left (Nm)	89.6 (40.1)	34.0-180.0
MIS in CRP right (Nm)	68.7 (30.3)	25.0-157.0
MIS in SAP extension (Nm)	165.5 (64.1)	76.0-364.0
MIS in SAP flexion (Nm)	83.2 (39.8)	29.0-184.0
MIS in rotation left (Nm)	61.6 (32.5)	17.0-139.0
MIS in rotation right (Nm)	60.1 (34.5)	12.0-140.0
Spinal mobility		
CRP spinal mobility ( $^{\circ}$ )	50.6 (12.6)	32.0-75.0
SAP spinal mobility ( $^{\circ}$ )	127.4 (16.7)	92.0-162.0
Static steady-state balance		
CoP <sub>sum</sub> (cm)	16.1 (5.3)	7.8-28.2
Dynamic steady-state balance		
Stride time (s)	1.02 (0.07)	0.89-1.20
Stride length (cm)	144.5 (11.2)	124.0-166.0
Stride velocity (cm/s)	141.8 (14.0)	128.0-165.0
Reactive balance		
SO <sub>sum</sub> (cm)	16.0 (4.9)	9.2-28.7
Proactive balance		
TUG (s)	9.4 (0.9)	7.8-11.7

*Note.* Values are means and standard deviations (in parentheses). *BMI* = body mass index; *CDT* = Clock Drawing Test; *CoP<sub>sum</sub>* = summed center of pressure (CoP) displacements in anterior-posterior and medio-lateral direction during step stance under steady-state balance conditions; *CRP* = coronal plane; *MIS* = maximal isometric strength; *MMSE* = Mini-Mental State Examination; *SAP* = sagittal plane; *SO<sub>sum</sub>* = summed oscillations (SO) in anterior-posterior and medio-lateral direction under reactive balance conditions; *TUG* = Timed Up and Go Test

### *Testing procedure*

Upon entering our biomechanical laboratory, all participants were kindly asked to answer the questions of three different questionnaires (i.e., Freiburg questionnaire for everyday and sports-related activities, MMSE, CDT). Thereafter, participants received standardized verbal

instructions regarding the test procedure with a visual demonstration of the TMS, spinal mobility, and the balance tests. Prior to testing, all participants performed between one and three practice trials on each test instrument to rule out potential learning effects. Thereafter, participants conducted a 10 min warm-up program on a bicycle ergometer at a rate of perceived exertion of 12 on the 6-20 Borg scale (Borg, 1982). Tests included (a) the measurement of static/dynamic steady-state, reactive, and proactive balance in a randomized sequence using a one-dimensional balance platform, an opto-electric walkway, a two-dimensional perturbation platform, and the Timed Up and Go Test (TUG); (b) the analysis of spinal mobility in the coronal (CRP) and the sagittal (SAP) plane using the MediMouse<sup>®</sup>-system (Lucamed International GmbH, Bad Säckingen, Germany); and (c) the assessment of maximal isometric strength (MIS) of the trunk flexors, extensors, lateral-flexors (right, left), and rotators (right, left) on an instrumented strength testing system (NORSK<sup>®</sup> system; NORSK, Ringsheim, Germany). This testing sequence was applied in order to keep the effects of neuromuscular fatigue minimal.

### *Questionnaire*

The Freiburg questionnaire for everyday and sports activities<sup>®</sup> (Frey, Berg, Grathwohl, & Keul, 1999) assesses basic physical activity level (e.g., gardening, climbing stairs), leisure time physical activity level (e.g., dancing, bowling), and sports activity level (e.g., jogging, swimming) of people between the ages of 18-78 years. Significant test-retest reliability was reported for the summed physical activity level ( $r = 0.56$ ). Cross-correlation with maximum oxygen uptake revealed a significant correlation coefficient of  $r = 0.42$  (Frey et al., 1999).

The MMSE is a valid test of cognitive function. It separates patients with cognitive disturbance from those without such disturbance. Test-retest reliability of the MMSE is high with  $r = 0.89$ . Cross-correlation with the Wechsler Adult Intelligence Scale revealed a correlation coefficient of  $r = 0.78$  (Folstein, Folstein, & McHugh, 1975). According to Lopez et al. (2005), a MMSE total score of 24 provides good sensitivity and specificity for the detection of dementia.

The CDT is a sensitive screening test for the evaluation of executive function (Thalman et al., 2002). The elderly participants were instructed to draw numbers in a given circle to make the circle look like a clock. Thereafter, subjects were asked to draw the hands of the clock to a point in time of their choice which, at the test's end, they had to write down in digital form. Depending on the study consulted, inter-rater reliability for the CDT ranges between 75.4-

99.6 % (Thalmann et al., 2002). Test-retest reliability can be classified as high with an  $r$  value of 0.90 (Manos & Wu, 1994). Cross-correlation with the MMSE revealed a correlation coefficient of  $r > 0.50$  (Shulman, 2000). As a result, the test distinguishes between pathological and normal test performance.

### *Apparatus*

#### *Trunk muscle strength (TMS) testing*

MIS of the trunk muscles was measured using four NORSK trunk testing machines (Ringsheim, Germany) that allowed the analysis of six different movement directions [i.e., flexion, extension, rotation in transversal plane (right, left), lateral bending (right, left)] (Paalanne et al., 2009). MIS was defined as the maximal voluntary strength (i.e., peak value of the force-time curve) determined under isometric condition. The participants were in a sitting position, with the thorax and the pelvis firmly fixed by straps or cushions around the shoulders, the waist, and the legs. All participants performed three maximal isometric contractions lasting 3-4 seconds in each direction of movement. Strength tests were conducted in a counterbalanced order and a 1 min rest was applied between the single tests. The mean of three test trials was used as an outcome measure. Bak, Anders, Bocker, & Smolenski (2003) reported excellent inter- and intrasession reliability in all movement directions. In addition, intraclass correlation coefficients (ICC) were calculated for MIS of the trunk muscles ranging from ICC = 0.89-0.96.

#### *Spinal mobility testing*

Spinal mobility was determined using the MediMouse<sup>®</sup> system (Lucamed International GmbH, Bad Säckingen, Germany), a hand-held, computer-assisted electromechanical device for measuring the spinal curvature in various postures (Guermazi et al., 2006). The device was guided along the midline of the spine starting at the spinous process of C7 and finishing at the top of the anal crease (approximately S3). These landmarks were determined by palpation and marked on the skin surface. Four test positions were performed: maximal extension, maximal flexion, maximal lateral flexion to the left and right side. Angles for the range of extension in the sagittal plane (SAP; maximal extension to flexion) and range of flexion in the coronal plane (CRP; maximal left to right flexion) were determined and used as outcome measures. ICC values were calculated for spinal mobility in the sagittal (ICC = 0.85) and the coronal

plane (ICC = 0.85). In addition, it was shown that the MediMouse<sup>®</sup> system has acceptable validity (i.e., assessed by radiography) in adults (Guermazi et al., 2006).

### *Balance testing*

Test circumstances (e.g., room illumination, temperature, noise) were in accordance with recommendations for posturographic testing (Kapteyn et al., 1983; Kressig & Beauchet, 2006).

### *Static steady-state balance*

Static steady-state balance was assessed by means of a balance platform (GKS 1000; IMM, Mittweida, Germany). The balance platform consists of four uniaxial sensors measuring displacements of the center of pressure (CoP) in the anterior-posterior and mediolateral directions. The balance platform was firmly fixed on the floor. For experimental testing, participants were asked to stand (i.e., tandem stance) in erect position with hands placed on hips and gaze fixated on a cross on the nearby wall. To avoid ceiling effects, subjects stood on an Airex<sup>®</sup> (Airex AG, Sins, Switzerland) balance pad (i.e., foam mat) to increase task difficulty. Subjects were instructed to remain as stable as possible and to refrain from any voluntary movements during the trials. Three test trials were conducted. The best trial (least CoP displacements) was used for further analysis. Data were acquired for 30 s at a sampling rate of 40 Hz (Kapteyn et al., 1983). Summed displacements of the center of pressure (CoP<sub>sum</sub> in cm) in anterior-posterior and mediolateral directions were computed and used as an outcome measure. ICC values were calculated for summed CoP displacements (ICC = 0.97).

### *Dynamic steady-state balance*

Dynamic steady-state balance was tested while walking on an instrumented 10-m walkway using the OptoGait<sup>®</sup> system (OptoGait, Bolzano, Italy). Participants walked with their own footwear at self-selected speeds, initiating and terminating each walk a minimum of 2 m before and after the 10-m walkway to allow sufficient distance to accelerate to and decelerate from a steady-state of ambulation across the walkway. The OptoGait<sup>®</sup> system is an optoelectrical measurement system consisting of a transmitting and a receiving bar. Each bar is 1 m in length and contains 100 LEDs that transmit continuously to each other. With a continuous connection between the two bars, any break in the connection can be measured and timed. The walking pattern was monitored at 1,000 Hz, enabling spatial and temporal gait data to be collected. The OptoGait<sup>®</sup> system demonstrated high discriminant and concurrent validity with

a validated electronic walkway (GAITRite<sup>®</sup> system; GAITRite, Franklin, USA) for the assessment of spatiotemporal gait parameters in orthopedic patients and healthy controls (Lienhard, Schneider, & Maffiuletti, 2013). Hausdorff, Edelberg, Mitchell, Goldberger, and Wei (1997) reported that spatiotemporal parameters of gait are important mobility markers in community-dwelling older adults. Thus, means and standard deviations (SD) of stride time, stride length, and stride velocity were computed. Stride time was defined as the time (s) between the first contacts of two consecutive footfalls of the same foot. Stride length was defined as the linear distance (cm) between successive heel contacts of the same foot. Additionally, stride velocity (cm/s) was calculated as stride length divided by stride time. Granacher, Bridenbaugh, Muehlbauer, Wehrle, and Kressig (2011) reported that ICC values for the calculated gait parameters were above 0.75.

### *Reactive balance*

It has been reported that older adults are particularly confronted with problems regarding balance recovery reactions when mediolateral perturbation impulses are applied (Maki & McIlroy, 1997). Further, observations from a video surveillance study of naturally occurring falls in elderly people showed specific problems in the control of laterally directed compensatory steps to avoid falling (Holliday, Fernie, Gryfe, & Griggs, 1990). Thus, a mediolateral perturbation impulse was applied while standing on a balance platform. During the test, participants stood in bipedal step stance on a two-dimensional balance platform (Posturomed; Haider Bioswing, Pullenreuth, Germany). The platform is mounted to four springs and is free to move in the transversal, anterior-posterior, and mediolateral directions. The maximal natural frequency of the Posturomed is below 3 Hz. The mechanical constraints and the reliability of the system were described earlier (Mueller, Gunther, Krauss, & Horstmann, 2004). If the platform is in neutral position, the maximum range of motion in the anterior-posterior and mediolateral directions amounts to 70 mm, respectively. The platform was moved 2.5 cm from the neutral position in the mediolateral direction, where it was magnetically fixed. For experimental testing, participants were asked to stand (i.e., step stance) in erect position with hands placed on hips and gaze fixated on a cross on the nearby wall. Three to five trials helped participants to get accustomed to the measuring device. After investigators visually controlled the position of the subjects, the mediolateral perturbation impulse was unexpectedly applied by detaching the magnet. The platform suddenly accelerated in the mediolateral direction. The participants' task was to damp the oscillating platform by balancing on the Posturomed. Summed oscilla-



tions ( $SO_{\text{sum}}$  in cm) of the platform in mediolateral and anterior-posterior directions were assessed by means of a joystick-like 2D potentiometer (Megatron, Munich, Germany) which was connected to the platform. The potentiometer measured the position of the platform in degree ( $^{\circ}$ ). The signal was differentiated, rectified, and integrated over the 10 s test interval. Three trials were performed. The best trial (least oscillations in mediolateral direction) was used for further analysis. Intraclass correlation coefficients were calculated for summed oscillations of the platform in anterior-posterior ( $ICC = 0.69$ ) and mediolateral ( $ICC = 0.40$ ) direction.

### *Proactive balance*

Proactive balance was analyzed by means of the TUG (Podsiadlo & Richardson, 1991). Participants were asked to perform the TUG at their self-selected normal speed. Before testing, a trained evaluator gave standardized verbal instructions regarding the test procedures. Participants were seated and instructed to walk 3 m, turn around, walk back to the chair and sit down. The stopwatch was started on the command “ready-set-go” and stopped as the participant sat down. Time was recorded with a stopwatch to the nearest 0.01 s. The TUG showed excellent test-retest reliability ( $ICC = 0.99$ ) in older adults (Podsiadlo & Richardson, 1991).

### *Statistical analyses*

Data are presented as group mean values  $\pm$  SD. Associations of strength and balance variables were assessed using Pearson product-moment correlation coefficient. Associations are reported by their correlation coefficient ( $r$  value), level of significance ( $p$  value), and the amount of variance explained ( $r^2$  value). Values of  $0.00 < r \leq 0.39$  indicate a small correlation, values of  $0.40 < r \leq 0.69$  indicate a medium correlation, and values of  $0.70 < r \leq 0.99$  indicate a large size of correlation (i.e., effect size [ES]) (Bös, Hänsel, & Schott, 2000). In addition, simple linear regression models were calculated to determine the most robust predictors of the respective outcome variables. The significance level was set at  $\alpha = 5\%$ . All analyses were performed using Statistical Package for Social Sciences (SPSS; IBM, Chicago, USA) version 21.0.

## Results

Anthropometric characteristics, measures of cognitive function, and variables in performance of TMS, spinal mobility, and balance are presented in Table 1.

### *Associations between measures of trunk muscle strength and balance*

Significant positive correlations were detected between all measures of TMS and static steady-state balance. The respective  $r$  values ranged from 0.43 to 0.57 (all  $p < 0.05$ ), which is indicative of medium ES (Table 2). Further, significant positive correlations were observed between specific measures of TMS (i.e., MIS in SAP [flexion and extension], MIS in trunk rotators [right, left]) and dynamic steady-state balance (i.e., stride length). Significant  $r$  values ranged from 0.42 to 0.55 (all  $p < 0.05$ ), which reveals medium ES (Table 2). However, no statistically significant associations were found between TMS and stride time as well as stride velocity ( $r \leq 0.28$ , all  $p > 0.05$ ; Table 2). In addition, no statistically significant correlations were found between all variables of TMS and reactive as well as proactive balance ( $r \leq 0.28$ , all  $p > 0.05$ ; Table 2).

**Table 2:** Associations between trunk muscle strength and balance (Pearson  $r_p$ ).

	<b>MIS in SAP extension</b>	<b>MIS in SAP flexion</b>	<b>MIS in CRP left</b>	<b>MIS in CRP right</b>	<b>MIS in rotation left</b>	<b>MIS in rotation right</b>
Static steady-state balance						
CoP <sub>sum</sub>	0.43*	0.45*	0.50**	0.51**	0.55**	0.57**
Dynamic steady-state balance						
Stride time	0.15	0.24	0.27	0.19	0.18	0.16
Stride length	0.52**	0.55**	0.29	0.16	0.42*	0.44*
Stride velocity	0.28	0.25	0.03	-0.02	0.17	0.21
Reactive balance						
SO <sub>sum</sub>	-0.01	0.12	0.09	0.02	0.21	0.17
Proactive balance						
TUG	-0.24	-0.28	-0.08	-0.15	-0.13	-0.13

*Note.* \* $p < 0.05$ ; \*\* $p < 0.01$ .  $CoP_{sum}$  = summed center of pressure (CoP) displacements in anterior-posterior and mediolateral direction during step stance under steady-state balance conditions;  $CRP$  = coronal plane;  $MIS$  = maximal isometric strength;  $SAP$  = sagittal plane;  $SO_{sum}$  = summed oscillations (SO) in anterior-posterior and medio-lateral direction under reactive balance conditions;  $TUG$  = Timed Up and Go Test

**Table 3:** Separate multivariate linear regression analyses for trunk muscle strength indices as predictors of various balance components.

<b>Outcome</b>	<b>Predictor</b>	<b>B</b>	<b>SE</b>	<b>Stand. est.</b>	<b>t value</b>	<b>p value</b>	<b>r<sup>2</sup></b>
Static steady-state balance (CoP <sub>sum</sub> )	MIS in CRP left	6.89	2.28	0.50	3.03	0.005	0.25
	MIS in CRP right	9.31	3.00	0.51	3.11	0.004	0.26
	MIS in SAP extension	3.56	1.43	0.43	2.49	0.019	0.18
	MIS in SAP flexion	5.86	2.21	0.45	2.66	0.013	0.20
	MIS in rotation left	8.79	2.49	0.55	3.53	0.001	0.31
	MIS in rotation right	8.62	2.33	0.57	3.70	0.001	0.33
Dynamic steady-state balance (stride length)	MIS in CRP left	0.08	0.05	0.30	1.79	0.083	0.09
	MIS in CRP right	0.06	0.06	0.17	0.99	0.331	0.03
	MIS in SAP extension	0.09	0.03	0.52	3.45	0.001	0.27
	MIS in SAP flexion	0.16	0.04	0.55	3.74	0.001	0.30
	MIS in rotation left	0.14	0.06	0.42	2.59	0.014	0.17
	MIS in rotation right	0.14	0.05	0.44	2.78	0.009	0.19
Reactive balance (SO <sub>sum</sub> )	MIS in CRP left	0.01	0.02	0.09	0.47	0.641	0.01
	MIS in CRP right	0.003	0.03	0.02	0.09	0.931	0.001
	MIS in SAP extension	-0.001	0.01	-0.01	-0.08	0.940	0.001
	MIS in SAP flexion	0.02	0.02	0.12	0.68	0.500	0.02
	MIS in rotation left	0.03	0.03	0.21	1.17	0.252	0.04
	MIS in rotation right	0.02	0.03	0.17	0.97	0.342	0.17

Table 3: continued

Outcome	Predictor	B	SE	Stand. est.	t value	p value	r <sup>2</sup>
Proactive balance (TUG)	MIS in CRP left	-0.001	0.004	-0.03	-0.19	0.849	0.03
	MIS in CRP right	-0.003	0.005	-0.12	-0.67	0.509	0.01
	MIS in SAP extension	-0.003	0.002	-0.18	-1.04	0.305	0.03
	MIS in SAP flexion	-0.006	0.004	-0.25	-1.46	0.155	0.06
	MIS in rotation left	-0.003	0.005	-0.12	-0.66	0.516	0.01
	MIS in rotation right	-0.003	0.005	-0.11	-0.61	0.549	0.01

*Note.*  $B$  = parameter estimate;  $CoP_{sum}$  = summed center of pressure (CoP) displacements in anterior-posterior and mediolateral direction during step stance under steady-state balance conditions;  $CRP$  = coronal plane;  $r^2$  = proportion of variance explained by the regression model (square of the standardized estimate in the present setting);  $SAP$  = sagittal plane;  $SE$  = standard error;  $SO_{sum}$  = summed oscillations (SO) in anterior-posterior and medio-lateral direction under reactive balance conditions; *Stand. est.* = standardized estimate (Pearson's correlation coefficient in the present setting);  $TUG$  = Timed Up and Go Test

Findings from the simple linear regression analysis for the predictor variables TMS and the criterion parameters balance control are represented in Table 3. The overall  $r^2$  values ranged from 0.01 to 0.33, explaining 1-33 % of total variance of the respective balance parameters. More specifically, explained variance for static steady-state balance ranged between 18 % and 33 % (all  $p < 0.05$ ; Table 3). For dynamic steady-state balance,  $r^2$  values ranged from 0.03 to 0.30 (i.e., explained variance 3-30 %; Table 3) with MIS in SAP explaining 27 % (extension) and 30 % (flexion) of total variance (both  $p < 0.01$ ), and MIS in rotation explaining 17 % (left) and 19 % (right) of total variance (both  $p < 0.05$ ). For reactive and proactive balance,  $r^2$  values ranged from 0.01 to 0.17 and from 0.01 to 0.06 indicating an explained variance of 1-17 % and 1-6 % (all  $p > 0.05$ ), respectively (Table 3). The covariates sex, body mass, body height, and body mass index did not influence our results (data not shown).

#### *Associations between measures of spinal mobility and balance*

Finally, no statistically significant correlations were detected between all variables of spinal mobility and balance performance ( $r \leq 0.23$ , all  $p > 0.05$ ; Table 4). Because no statistically significant correlations were found between spinal mobility and balance, we did not calculate linear regression models for these measures.

**Table 4:** Associations between spinal mobility and balance (Pearson  $r_p$ ).

	<b>SAP spinal mobility</b>	<b>CRP spinal mobility</b>
Static steady-state balance	0.00	0.03
CoP <sub>sum</sub>	0.03	0.01
Dynamic steady-state balance		
Stride time	-0.10	0.02
Stride length	-0.12	-0.01
Stride velocity	-0.05	-0.03
Reactive balance		
SO <sub>sum</sub>	-0.19	-0.16
Proactive balance		
TUG	-0.08	-0.23

$CoP_{sum}$  = summed center of pressure (CoP) displacements in anterior-posterior and mediolateral direction during step stance under steady-state balance conditions;  $CRP$  = coronal plane;  $SAP$  = sagittal plane;  $SO_{sum}$  = summed oscillations (SO) in anterior-posterior and medio-lateral direction under reactive balance conditions;  $TUG$  = Timed Up and Go Test

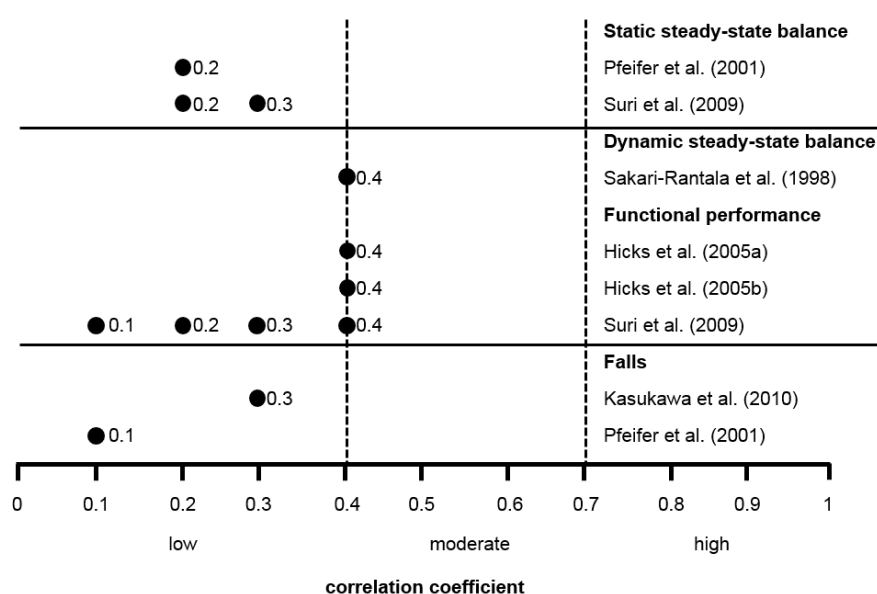
## Discussion

This is the first study that investigated in a methodologically comprehensive approach potential associations between various measures of TMS (i.e., flexion, extension, lateral flexion, and rotation), balance (i.e., steady-state, reactive, and proactive balance), and spinal mobility (i.e., flexion, extension, and lateral flexion) in cognitively healthy and physically active older adults. The main findings can be summarized as follows: (1) statistically significant medium size correlations were observed between all measures of TMS and static steady-state balance; (2) statistically significant medium size correlations were observed between specific measures of TMS and dynamic steady-state balance; (3) no statistically significant correlations were found between all variables of TMS and reactive as well as proactive balance; and (4) no statistically significant associations were detected between all variables of spinal mobility and balance performance.

### *Associations between measures of trunk muscle strength and balance*

Figure 1 illustrates that our findings comply with the literature regarding the observed associations between measures of TMS and balance in old age. More specifically, Figure 1 denotes small to medium effect sizes for variables of TMS, trunk muscle composition, balance, functional performance, and falls. Our statistically significant correlations were in the range of 0.42-0.57 and thus slightly above those reported in Figure 1. Notably, the results from the present study go beyond the findings reported in the literature in as much as we were able to show relations between TMS and various balance components (i.e., static and dynamic steady-state balance). In fact, our results indicate that particularly trunk muscle flexor, extensor, and rotator strength are associated with static steady-state balance, with specific variables of dynamic steady-state balance but not with reactive and proactive balance. Given that correlative analyses do not permit the identification of cause-and-effect relationships, care is needed when functionally interpreting these findings. Nevertheless, it can be hypothesized that exercises particularly for the trunk muscle extensors, flexors, and rotators should be incorporated in resistance training programs to promote static and dynamic steady-state balance in older adults. More specifically, since significant medium sized correlations were found between maximal trunk muscle flexor, extensor, and rotator strength and specific variables of balance, it appears that TMS exercises should be conducted at high intensities to enhance balance. This important issue however needs further verification. Due to the fact that measures of TMS and reactive as well as proactive balance did not significantly correlate, it seems reason-

able to argue that specific exercises for the promotion of reactive and proactive balance should be incorporated in a comprehensive fall-preventive balance and resistance training program. To translate these findings in a larger context, there is clear evidence from a recently published systematic review that trunk muscle training (i.e., core strength training, Pilates exercise training) is effective in improving balance and functional performance in older adults (Granacher et al., 2013). Further, it has been shown that core strength training is feasible and safe. In fact, following nine weeks of core instability strength training, Granacher, Lacroix, Muehlbauer, Roettger, and Gollhofer (2013) reported excellent program compliance in the intervention group (i.e., 92 % attendance rate) and no training-related injuries.



**Figure 1:** Relationship between trunk muscle strength/composition and static steady-state balance, dynamic steady-state balance, and falls in older adults as reported in the literature.

What might be the underlying reason for the observed significant correlations between measures of maximal isometric TMS and static/dynamic steady-state balance? It can be hypothesized that older adults with high levels of TMS may use their upper and lower extremities more effectively during standing and walking due to a stable trunk which is the mechanical linkage between upper and lower extremities. In fact, trunk stability is provided by coactivation of global (e.g., rectus abdominis, external obliques) and local muscles (e.g., transverse abdominis, lumbar multifidus). Global muscles primarily produce torque and transfer load between the thoracic cage and the pelvis, whereas local muscles are associated with segmental

stability of the lumbar spine during whole body movements and postural adjustments (Bergmark, 1989). In this study, statistically significant medium sized correlations were found between measures of maximal isometric TMS and specific variables of static/dynamic steady-state balance. Given that global muscles are primarily responsible for torque production and transfer of load (Bergmark, 1989), our results indicate that they additionally contribute to mechanical stability of the trunk. Bergmark (1989) provides an explanation for the stabilizing role of the global system by arguing that global muscles balance external loads (e.g., produced through limb movements) so that the resulting force transferred to the lumbar spine can be controlled by the local muscles. Thus, global muscles may indirectly influence the stability conditions of the trunk. In support of this hypothesis, different authors (Aruin & Latash, 1995; Hodges & Richardson, 1997) have identified contractions of the rectus abdominis and the erector spinae (both global muscles) in advance of upper and lower limb flexion and extension movements. In this regard, anticipatory trunk muscle contractions seem to be necessary to ensure spinal/postural stability against reactive forces resulting from limb movements (Hodges & Richardson, 1999). In summary, adequate levels of TMS appear to be necessary for maintaining upright posture (i.e., static balance) and ensuring stability during walking (i.e., dynamic balance).

#### *Associations between measures of spinal mobility and balance*

In a cross-sectional study, Schenkman et al. (1996) observed that as age increases, cervical and lumbar mobility decrease. It has further been shown that spinal deformity together with reduced lower limb and trunk muscle strength plays an important role in increasing body sway, gait unsteadiness, and risk of falls in community-dwelling older women with osteoporosis (Sinaki, Brey, Hughes, Larson, & Kaufman, 2005). Based on these findings, it was initially hypothesized that there should also be a significant relation between measures of spinal mobility and balance. However, the present study revealed small and nonsignificant associations between measures of spinal mobility and variables of static/dynamic steady-state, reactive, and proactive balance in healthy community-dwelling older adults. It appears that age and physical mobility status may play a moderating role in terms of the association between spinal mobility and balance. In terms of age, it is argued that decreased acute spinal mobility might be a precursor of spinal deformity which is again moderated by TMS (Mika, Fernhall, & Mika, 2009). In terms of physical mobility status, it appears that acute spinal mobility is associated with falls in mobility-impaired and fall-prone older adults (Kasukawa et al., 2010)



but not in healthy community-dwelling older adults. In fact, using multiple logistic regression analysis, Kasukawa et al. (2010) found significant associations between back extensor strength ( $p = 0.005$ ), lumbar kyphosis ( $p = 0.006$ ), spinal inclination ( $p = 0.038$ ), mobility of lumbar spine ( $p = 0.027$ ), and mobility of spinal inclination ( $p = 0.028$ ) with presence/absence of falls in mobility-impaired elderly individuals. The present study could not confirm these findings for healthy and physically active community-dwelling older adults. Nevertheless, spinal mobility can be used as a predictor of quality of life in patients with postmenopausal osteoporosis (Miyakoshi et al., 2007) as well as in healthy middle-aged and elderly males (Imagama et al., 2011). In summary, assuming that impaired spinal mobility is a precursor of chronic spinal deformity, it is argued that tests for the assessment of spinal mobility and exercises for the promotion of spinal mobility should specifically be applied in older and mobility-impaired adults.

We acknowledge that this study has some limitations that warrant discussion. More specifically, the participants included in this study were healthy physically active older adults. Therefore, caution is needed when generalizing the present findings to other populations (e.g., mobility-limited subjects or patients). In addition, the results of this study are specific to the testing methodology used to assess TMS, spinal mobility, and balance performance. These measures may not represent all components of strength, mobility, and balance. Therefore, caution is needed when generalizing the present findings to other testing situations.

## **Conclusions**

This study revealed statistically significant medium sized correlations between all measures of TMS and static steady-state balance and specific measures of TMS and dynamic steady-state balance. From a functional point of view, these findings imply that in healthy, physically active older adults, TMS could be used to predict static and dynamic steady-state balance performance. Moreover, gains made in TMS after resistance training may be associated with a change in static and dynamic steady-state balance performance. Therefore, TMS promoting exercises should be integrated in resistance training programs for older adults. In addition, small (however, not statistically significant) correlations were found for all variables of TMS and reactive as well as proactive balance, and for all variables of spinal mobility and balance performance. This implies that these performances are independent of each other and may have to be tested and trained complementarily.

## References

- Abe, T., Sakamaki, M., Yasuda, T., Bembem, M. G., Kondo, M., Kawakami, Y., & Fukunaga, T. (2011). Age-related, site-specific muscle loss in 1507 Japanese men and women aged 20 to 95 years. *Journal of Sports Science and Medicine*, *10*(1), 145-150.
- Aruin, A. S., & Latash, M. L. (1995). Directional Specificity of Postural Muscles in Feedforward Postural Reactions during Fast Voluntary Arm Movements. *Experimental Brain Research*, *103*(2), 323-332.
- Bak, P., Anders, C., Bocker, B., & Smolenski, U.C. (2003). [Reliability of the measurement of isometric maximal voluntary contraction of trunk muscles in healthy subjects]. *Physikalische Medizin, Rehabilitationsmedizin, Kurortmedizin*, *13*(1), 28-34. doi: 10.1055/s-2003-37669
- Balzini, L., Vannucchi, L., Benvenuti, F., Benucci, M., Monni, M., Cappozzo, A., & Stanhope, S. J. (2003). Clinical characteristics of flexed posture in elderly women. *Journal of the American Geriatrics Society*, *51*(10), 1419-1426.
- Bergmark, A. (1989). Stability of the lumbar spine. A study in mechanical engineering. *Acta orthopaedica Scandinavica. Supplementum*, *230*, 1-54.
- Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377-381.
- Bös, K., Hänsel, F., & Schott, N. (2000). *Empirische Untersuchungen in der Sportwissenschaft*. Hamburg: Czwalina Verlag.
- Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189-198.
- Frey, I., Berg, A., Grathwohl, D., & Keul, J. (1999). Freiburg Questionnaire of physical activity - development, evaluation and application. *Soziale Präventivmedizin*, *44*(2), 55-64.
- Granacher, U., Bridenbaugh, S. A., Muehlbauer, T., Wehrle, A., & Kressig, R. W. (2011). Age-related effects on postural control under multi-task conditions. *Gerontology*, *57*(3), 247-255. doi: 10.1159/000322196
- Granacher, U., Gollhofer, A., Hortobagyi, T., Kressig, R. W., & Muehlbauer, T. (2013). The importance of trunk muscle strength for balance, functional performance, and fall prevention in seniors: a systematic review. *Sports Medicine*, *43*(7):627-41. doi: 10.1007/s40279-013-0041-1
- Granacher, U., Lacroix, A., Muehlbauer, T., Roettger, K., & Gollhofer, A. (2013). Effects of core instability strength training on trunk muscle strength, spinal mobility, dynamic balance and functional mobility in older adults. *Gerontology*, *59*(2), 105-113. doi: 10.1159/000343152
- Guerhazi, M., Ghroubi, S., Kassis, M., Jaziri, O., Keskes, H., Kessomtini, W., . . . Elleuch, M. H. (2006). Validity and reliability of Spinal Mouse to assess lumbar flexion. *Annales De Readaptation Et De Medecine Physique*, *49*(4), 172-177. doi: 10.1016/j.annrmp.2006.03.001
- Haemaelaeninen, P., Suni, J., Pasanen, M., Malmberg, J., & Miilunpalo, S. (2006). Changes in physical performance among high-functioning older adults: a 6-year follow-up study. *European Journal of Ageing*, *3*(1), 3-14. doi: 10.1007/s10433-006-0018-0
- Hausdorff, J. M., Edelberg, H. K., Mitchell, S. L., Goldberger, A. L., & Wei, J. Y. (1997). Increased gait unsteadiness in community-dwelling elderly fallers. *Archives of Physical Medicine and Rehabilitation*, *78*(3), 278-283.

- Hicks, G. E., Simonsick, E. M., Harris, T. B., Newman, A. B., Weiner, D. K., Nevitt, M. A., & Tylavsky, F. A. (2005a). Cross-sectional associations between trunk muscle composition, back pain, and physical function in the health, aging and body composition study. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *60*(7), 882-887.
- Hicks, G. E., Simonsick, E. M., Harris, T. B., Newman, A. B., Weiner, D. K., Nevitt, M. A., & Tylavsky, F. A. (2005b). Trunk muscle composition as a predictor of reduced functional capacity in the health, aging and body composition study: the moderating role of back pain. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *60*(11), 1420-1424.
- Hodges, P. W., & Richardson, C. A. (1997). Contraction of the abdominal muscles associated with movement of the lower limb. *Physical Therapy*, *77*(2), 132-142.
- Hodges, P. W., & Richardson, C. A. (1999). Transversus abdominis and the superficial abdominal muscles are controlled independently in a postural task. *Neuroscience Letters*, *265*(2), 91-94. doi: 10.1016/S0304-3940(99)00216-5
- Holliday, P. J., Fernie, G. R., Gryfe, C. I., & Griggs, G. T. (1990). Video recording of spontaneous falls of the elderly. In B.E. Gray (Ed.), *Slips, stumbles, and falls: pedestrian footwear and surfaces* (pp. 7-16). Philadelphia, USA: American Society for Testing and Materials.
- Imagama, S., Matsuyama, Y., Hasegawa, Y., Sakai, Y., Ito, Z., Ishiguro, N., & Hamajima, N. (2011). Back muscle strength and spinal mobility are predictors of quality of life in middle-aged and elderly males. *European Spine Journal*, *20*(6), 954-961. doi: 10.1007/s00586-010-1606-4
- Kapteyn, T. S., Bles, W., Njikiktjien, C. J., Kodde, L., Massen, C. H., & Mol, J. M. (1983). Standardization in platform stabilometry being a part of posturography. *Agressologie*, *24*(7), 321-326.
- Kasukawa, Y., Miyakoshi, N., Hongo, M., Ishikawa, Y., Noguchi, H., Kamo, K., . . . Shimada, Y. (2010). Relationships between falls, spinal curvature, spinal mobility and back extensor strength in elderly people. *Journal of Bone and Mineral Metabolism*, *28*(1), 82-87. doi: 10.1007/s00774-009-0107-1
- Kressig, R. W., & Beauchet, O. (2006). Guidelines for clinical applications of spatio-temporal gait analysis in older adults. *Aging Clinical and Experimental Research*, *18*(2), 174-176.
- Lienhard, K., Schneider, D., & Maffioletti, N. A. (2013). Validity of the Optogait photoelectric system for the assessment of spatiotemporal gait parameters. *Medical Engineering & Physics*, *35*(4), 500-504. doi: 10.1016/j.medengphy.2012.06.015
- Lopez, M., Charter, R., Mostafavi, B., Nibut, L., & Smith, W. (2005). Psychometric properties of the folstein mini-mental state examination. *Assessment*, *12*(2), 137-144. doi: 10.1177/1073191105275412
- Maki, B. E., & McIlroy, W. E. (1997). The role of limb movements in maintaining upright stance: the “change-in-support” strategy. *Physical Therapy*, *77*(5), 488-507.
- Manos, P. J., & Wu, R. (1994). The ten point clock test: a quick screen and grading method for cognitive impairment in medical and surgical patients. *International Journal of Psychiatry in Medicine*, *24*(3), 229-244. doi: 10.2190/5A0F-936P-VG8N-0F5R
- Mika, A., Fernhall, B., & Mika, P. (2009). Association between moderate physical activity, spinal motion and back muscle strength in postmenopausal women with and without osteoporosis. *Disability and Rehabilitation*, *31*(9), 734-740. doi: 10.1080/09638280802308998

- Miyakoshi, N., Hongo, M., Maekawa, S., Ishikawa, Y., Shimada, Y., & Itoi, E. (2007). Back extensor strength and lumbar spinal mobility are predictors of quality of life in patients with postmenopausal osteoporosis. *Osteoporosis International*, *18*(10), 1397-1403. doi: 10.1007/s00198-007-0383-3
- Mueller, O., Gunther, M., Krauss, I., & Horstmann, T. (2004). [Physical characterization of the therapeutic device posturomed as a measuring device presentation of a procedure to characterize balancing ability]. *Biomedizinische Technik*, *49*(3), 56-60. doi: 10.1515/Bmt.2004.011
- Paalanne, N. P., Korpelainen, R., Taimela, S. P., Remes, J., Salakka, M., & Karppinen, J. I. (2009). Reproducibility and reference values of inclinometric balance and isometric trunk muscle strength measurements in Finnish young adults. *Journal of Strength and Conditioning Research*, *23*(5), 1618-1626. doi: 10.1519/JSC.0b013e3181a3cdfc
- Pfeifer, M., Begerow, B., Minne, H. W., Schlotthauer, T., Pospeschill, M., Scholz, M., . . . Pollahne, W. (2001). Vitamin D status, trunk muscle strength, body sway, falls, and fractures among 237 postmenopausal women with osteoporosis. *Experimental and Clinical Endocrinology & Diabetes*, *109*(2), 87-92. doi: 10.1055/s-2001-14831
- Podsiadlo, D., & Richardson, S. (1991). The timed "Up & Go": a test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society*, *39*(2), 142-148.
- Ryan, S. D., & Fried, L. P. (1997). The impact of kyphosis on daily functioning. *Journal of the American Geriatrics Society*, *45*(12), 1479-1486.
- Sakari-Rantala, R., Era, P., Rantanen, T., & Heikkinen, E. (1998). Associations of sensory-motor functions with poor mobility in 75- and 80-year-old people. *Scandinavian Journal of Rehabilitation Medicine*, *30*(2), 121-127.
- Schenkman, M., Shipp, K. M., Chandler, J., Studenski, S. A., & Kuchibhatla, M. (1996). Relationships between mobility of axial structures and physical performance. *Physical Therapy*, *76*(3), 276-285.
- Shulman, K. I. (2000). Clock-drawing: is it the ideal cognitive screening test? *International Journal of Geriatric Psychiatry*, *15*(6), 548-561.
- Sinaki, M., Brey, R. H., Hughes, C. A., Larson, D. R., & Kaufman, K. R. (2005). Balance disorder and increased risk of falls in osteoporosis and kyphosis: significance of kyphotic posture and muscle strength. *Osteoporosis International*, *16*(8), 1004-1010. doi: 10.1007/s00198-004-1791-2
- Suri, P., Kiely, D. K., Leveille, S. G., Frontera, W. R., & Bean, J. F. (2009). Trunk muscle attributes are associated with balance and mobility in older adults: a pilot study. *PM & R*, *1*(10), 916-924. doi: 10.1016/j.pmrj.2009.09.009
- Thalmann, B., Spiegel, R., Stähelin, H. B., Brubacher, D., Ermini-Fünfschilling, D., Bläsi, S., & Monsch, A. U. (2002). Dementia screening in general practice: optimised scoring for the clock drawing test. *Brain Aging*, *2*(2), 36-43.
- Viitasalo, J. T., Era, P., Leskinen, A. L., & Heikkinen, E. (1985). Muscular strength profiles and anthropometry in random samples of men aged 31-35, 51-55 and 71-75. *Ergonomics*, *28*(11), 1563-1574. doi: 10.1080/00140138508963288

## Publication II

### **A BEST PRACTICE FALL PREVENTION EXERCISE PROGRAM TO IMPROVE BALANCE, STRENGTH/POWER, AND PSYCHOSOCIAL HEALTH IN OLDER ADULTS: STUDY PROTOCOL FOR A RANDOMIZED CONTROLLED TRIAL**

Yves J. Gschwind<sup>1</sup>, Reto W. Kressig<sup>2</sup>, André Lacroix<sup>3</sup>, Thomas Muehlbauer<sup>3</sup>, Barbara Pfenninger<sup>4</sup> & Urs Granacher<sup>3</sup>

<sup>1</sup> Basel Mobility Center, University Hospital Basel, University Center for Medicine of Aging Basel, Basel Switzerland

<sup>2</sup> University of Basel and Felix Platter-Hospital Basel, University Center for Medicine of Aging Basel, Basel, Switzerland

<sup>3</sup> Division of Training and Movement Science, University of Potsdam, Potsdam, Germany

<sup>4</sup> Swiss Council for Accident Prevention, Bern, Switzerland

## Reference

Gschwind, Y. J., Kressig, R. W., Lacroix, A., Muehlbauer, T., Pfenninger, B., & Granacher, U. (2013). A best practice fall prevention exercise program to improve balance, strength/power, and psychosocial health in older adults: study protocol for a randomized controlled trial. *BMC Geriatrics*, *13*, 105. doi: 10.1186/1471-2318-13-105

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## Abstract

### *Background*

With increasing age neuromuscular deficits (e.g., sarcopenia) may result in impaired physical performance and an increased risk for falls. Prominent intrinsic fall risk factors are age-related decreases in balance and strength/power performance as well as cognitive decline. Additional studies are needed to develop specifically tailored exercise programs for older adults that can easily be implemented into clinical practice. Thus, the objective of the present trial is to assess the effects of a fall prevention program that was developed by an interdisciplinary expert panel on measures of balance, strength/power, body composition, cognition, psychosocial well-being, and falls self-efficacy in healthy older adults. Additionally, the time-related effects of detraining are tested.

### *Methods/Design*

Healthy old people ( $N = 54$ ) between the age of 65 to 80 years will participate in this trial. The testing protocol comprises tests for the assessment of static/dynamic steady-state balance (i.e., Sharpened Romberg Test, instrumented gait analysis), proactive balance (i.e., Functional Reach Test; Timed Up and Go Test), reactive balance (i.e., perturbation test during bipedal stance; Push and Release Test), strength (i.e., hand grip strength test; Chair Stand Test), and power (i.e., Stair Climb Power Test; countermovement jump). Further, body composition will be analysed using a bioelectrical impedance analysis system. In addition, questionnaires for the assessment of psychosocial (i.e., World Health Organisation Quality of Life Assessment-Bref), cognitive (i.e., Mini Mental State Examination), and fall risk determinants (i.e., Falls Efficacy Scale – International) will be included in the study protocol. Participants will be randomized into two intervention groups or the control/waiting group. After baseline measures, participants in the intervention groups will conduct a 12-week balance and resistance/power exercise intervention 3 times per week, with each training session lasting 30 min. (actual training time). One intervention group will complete an extensive supervised training program, while the other intervention group will complete a short version ('3 times 3') that is home-based and controlled by weekly phone calls. Post-tests will be conducted right after the intervention period. Additionally, detraining effects will be measured 12 weeks after program cessation. The control group/waiting group will not participate in any specific intervention

during the experimental period, but will receive the extensive supervised program after the experimental period.

### *Discussion*

It is expected that particularly the supervised combination of balance and resistance training will improve performance in variables of balance, strength/power, body composition, cognitive function, psychosocial well-being, and falls self-efficacy of older adults. In addition, information regarding fall risk assessment, dose-response-relations, detraining effects, and supervision of training will be provided. Further, training-induced health-relevant changes, such as improved performance in activities of daily living, cognitive function, and quality of life, as well as a reduced risk for falls may help to lower costs in the health care system. Finally, practitioners, therapists, and instructors will be provided with a scientifically evaluated feasible, safe, and easy-to-administer exercise program for fall prevention.

### *Trial registration*

ClinicalTrials.gov Identifier: NCT01906034

**Keywords:** seniors; fall risk assessment; resistance training; postural stability

## Background

Worldwide, the number of people over 60 years is growing faster than any other age group and expected to grow from 688 million in 2006 to almost 2 billion by 2050 (World Health Organization, 2007). The main reasons for this substantial demographic change are higher life expectancy and declining birth rates (McCallum, 2011). This future increase in the proportion of older adults is important from a public health perspective (Sherrington, Tiedemann, Fairhall, Close, & Lord, 2011). Aging is generally associated with progressive decline in physical and psychological health (Henderson, Irving, & Nair, 2009; Latham et al., 2003), increased risk of disability and dependency (Latham et al., 2003), as well as an increase in the number of comorbidities (Muehlberg & Sieber, 2004). This decrease in health status is mainly responsible for one of the most common and serious public health problems, namely falls. Over 33 % of community-dwelling people aged over 65 years fall at least once a year, and of those 50 % will have recurrent falls (Moreland et al., 2003; Rubenstein, 2006). With increasing age, the rate of falls can increase up to 60 % (Rubenstein, 2006; Rubenstein & Josephson, 2002). Older adults suffering from cognitive decline may fall twice as often compared to their healthy counterparts (Taylor, Delbaere, Mikolaizak, Lord, & Close, 2013), while institutionalized older adults in nursing homes or old people's homes fall even more often (Gostynski, Ajdacic-Gross, Gutzwiller, Michel, & Herrmann, 1999).

Despite frequent falling in older adults, only one in five falls requires medical attention while less than 10% lead to a fracture (Gillespie et al., 2012). However, in terms of morbidity and mortality, injurious falls have serious consequences of which the hip fracture is the most feared one (Lee et al., 2012). Hip fractures often affect functionality and autonomy of older adults (Brewer, Kelly, Donegan, Moore, & Williams, 2011), and are associated with an overall mortality of 22 % to 29 % one year after injury (Haleem, Lutchman, Mayahi, Grice, & Parker, 2008). In this context, 27 % of older adults require a walking aid one year after a hip fracture surgery (Pretto et al., 2010). Despite rehabilitation, many individuals do not regain the level of functional performance they had before the fracture (Brewer et al., 2011), which is why fall prevention is important.

Detection of fall risk factors is essential to implement effective and specifically tailored fall prevention strategies (Axer, Axer, Sauer, Witte, & Hagemann, 2010). Some fall risk factors are irreversible while others are potentially modifiable with appropriate interventions (Lord, Sherrington, Menz, & Close, 2007; American Geriatrics Society, British Geriatrics Society, & American Academy of Orthopaedic Surgeons Panel on Falls Prevention, 2001). Regularly



conducted objective, reliable and valid fall risk assessment protocols can assist in identifying individuals at risk to make recommendations and optimize prevention strategies (Bloch et al., 2013). Three of the most common modifiable intrinsic (subject-related) fall risk factors are muscle weakness (relative risk ratio/odds ratio 4.4), balance deficits (relative risk ratio/odds ratio 2.9), and gait instabilities (relative risk ratio/odds ratio 2.9) (American Geriatrics Society et al., 2001; Granacher, Muehlbauer, Zahner, Gollhofer, & Kressig, 2011; Rubenstein & Josephson, 2002). These intrinsic risk factors may be modified by exercise referred to as structured, planned and repetitive physical activities in community-based organized exercise programs (Franklin et al., 2013; Koeneman, Verheijden, Chinapaw, & Hopman-Rock, 2011).

Balance is important for maintaining postural equilibrium and thus for the avoidance of falls. Aging may affect central nervous system (i.e., changes in brain volume) and neuromuscular system properties (i.e., loss of sensory and motor neurons) leading to deficits in balance and gait performance (Granacher, Muehlbauer, & Gruber, 2012). According to Shumway-Cook and Woollacott (2007) balance can be subdivided into static/dynamic steady-state (i.e., maintaining a steady position in sitting, standing and walking), proactive (i.e., anticipation of a predicted disturbance), and reactive (i.e., compensation of a disturbance) balance (Muehlbauer, Besemer, Wehrle, Gollhofer, & Granacher, 2012; Sturnieks et al., 2012). Recently, Muehlbauer et al. (2012) were able to show that there is no significant association between measures of steady-state, proactive, and reactive balance in healthy older adults. Thus, for testing and training purposes, balance tests and exercises should target all three domains separately and additionally include dual- or multi-task situations (Muehlbauer et al., 2012), given that multi-tasking is required for the performance of many activities of daily living (ADL, e.g., walking downstairs while talking on the phone) (Krampe, Rapp, Bondar, & Baltes, 2003; Weksler & Weksler, 2012). Furthermore, specific balance exercises may help to counteract balance deficits and gait instabilities by reducing the risk of falls in older adults (Granacher et al., 2010; Shumway-Cook, Gruber, Baldwin, & Liao, 1997; Sturnieks, St George, & Lord, 2008; Tiedemann, Sherrington, Close, & Lord 2011).

Besides balance, muscle strength/power is required for the successful performance of ADL (Muehlbauer et al., 2012). General causes of age-related skeletal muscle mass loss (i.e., sarcopenia) are manifold (e.g., cellular, neural, metabolic, hormonal contributors) (Clark & Marini, 2008; Henderson et al., 2009; Howley & Don Franks, 2003). For the diagnosis of age-related sarcopenia the European Working Group on Sarcopenia in Older People (EWGSOP) recommends using the criteria low muscle mass plus either low muscle strength or low physi-

cal performance measured by gait velocity ( $\leq 80$  cm/s), grip strength and muscle mass (Dodds & Sayer, 2014). Humans lose approximately 20 % to 30 % of their skeletal muscle mass between young adulthood and 80 years of age (Carmeli, Coleman, & Reznick, 2002). This loss in muscle fiber size and number predominantly occurs in type II muscle fibers which lead to a more rapid decline in muscle power compared to overall muscle strength (Reid et al., 2008). This is detrimental because muscle power is an important prerequisite for quick postural reactions in response to external perturbations (Henwood & Taaffe, 2005). Older adults often use the hip or step strategy when balance is threatened (Rubenstein, 2006; Sturnieks et al., 2008). A decrease in muscle power would delay such postural reactions to external perturbations (Woollacott & Shumway-Cook, 1990; Ceglia, 2009), probably leading to a loss of balance (Orr et al., 2006) and ultimately resulting in a fall (Rubenstein, 2006).

Based on a thorough fall risk assessment, specifically tailored balance and resistance training programs can be developed which have the potential to improve important intrinsic fall risk factors like deficits in muscle strength/power and balance performance (Sturnieks et al., 2012). For fall prevention, exercises for the promotion of static/dynamic steady-state, proactive and reactive balance should be trained complementarily (Granacher et al., 2012). Progression during training can be achieved by reducing the base of support (e.g., bipedal, step, tandem, monopodal stance) and by diminishing the sensory input (e.g., exercises with eyes opened/closed; exercises on stable/unstable surfaces) (Granacher, Muehlbauer, Gollhofer, Kressig, & Zahner, 2011; Granacher, Muehlbauer, Zahner et al., 2011). Additionally, resistance training with a focus on muscle strength/power for the lower extremities and the trunk muscles (Granacher, Gollhofer, Hortobagyi, Kressig, & Muehlbauer, 2013) seems essential for counteracting intrinsic fall risk factors (i.e., muscle weakness) in older adults.

During the past decades, many fall prevention interventions have proven a positive effect of exercise on intrinsic fall risk factors (Gillespie et al., 2012). Despite substantial evidence, these programs have not been sufficiently implemented into clinical practice (Lord, Sherrington, Cameron, & Close, 2011). To reduce the burden of falls in older adults, easy-to-administer fall prevention programs need to be developed and implemented nationwide. However, lack of skilled people, inadequate communication between researchers, policy makers and clinicians, and health system barriers including inadequate financial resources hinder the implementation of new research evidence into practice (Gschwind, Wolf, Bridenbaugh, & Kressig, 2011; Lord et al., 2011). Besides a lack of evidence about how fall prevention can be incorporated into community services (Day, 2013), there is hardly any data available regard-

ing dose-response relationships for optimal exercise for fall prevention. Hence, the Swiss Council for Accident Prevention (bfu) convened an international expert panel ( $N = 8$ ) consisting of geriatricians, physiotherapists, and health, sports, exercise, accident and fall prevention scientists to conceptualize optimal balance and resistance training programs for fall prevention in older adults. The professional knowledge of the expert panel, the framework of the Manual for Falls Prevention Classification System from the Prevention of Falls Network Europe (ProFaNE), and recent state-of-the-art research, especially in a Swiss context, built the basis for the production of a cost-free practice guide open to the public (available in German or French: <http://www.stuerze.bfu.ch>) (Gillespie et al., 2012; Gschwind et al., 2011; ProFaNE, 2007).

The proposed trial presented in this article will investigate the effects of a fall prevention exercise program developed by an expert panel on intrinsic fall risk factors (i.e., balance, strength/power), body composition, cognitive function, psychosocial well-being, and falls self-efficacy. The applied research tools will allow diagnosis of sarcopenia according to the EWGSOP guidelines. Thus, we will be able to evaluate prevalence of sarcopenia in our participants, and conduct sensitivity and specificity analysis for the strength/power assessments including their cut-offs. To facilitate transfer into clinical practice, simple clinical tests for each instrumented test will be provided to alleviate fall risk assessment and exercise prescription adjustment. In addition to an easy implementation into practice, this will allow cross-validation of the applied research instruments (clinical vs. instrumented). Further, this work may help to promote the protocol of the expert panel and the rationale behind the practice guide to people with English as their native language. We hypothesize that our training program will positively influence balance, strength/power, body composition as well as cognition, psychosocial well-being, and falls self-efficacy in older community-dwelling people.

## **Methods/Design**

### *Participants*

Community-dwelling older adults aged 65 to 80 years without neurophysiologic diseases will be included in this single center, randomized, controlled study. Figure 1 shows a flow chart of the study design. Eligibility will be screened with the Standard Assessment Protocol of the Acute Geriatrics Department at the University Hospital Basel/Felix Platter-Hospital Basel including demographic, anthropometric and medical data to rule out contraindications to ex-

ercise. Participants will be excluded when they reach cut-off scores for the following tests: Mini Mental State Examination score (MMSE; < 24 points) (Folstein, Folstein, & McHugh, 1975; Lopez, Charter, Mostafavi, Nibut, & Smith, 2005), Clock Drawing Test (CDT; pathological test performance) (Thalman et al., 2002), Tuning Fork test (individual vibration threshold) (Pestronk et al., 2004), Falls Efficacy Scale-International (FES-I; > 24 points) (Dias et al., 2006), World Health Organization Quality of Life Assessment-Bref (WHOQOL-Bref) (Greenberg, 2007), and the Freiburg Questionnaire of Physical Activity (FQoPA; less than 1 hour of everyday and sports-related physical activity per week) (Frey, Berg, Grathwohl, & Keul, 1999). Evidence showed that even sedentary older adults are not at increased risk for injury when performing an exercise program compared to young adults (Little, Paterson, Humphreys, & Stathokostas, 2013). Written informed consent will be obtained from all older adults prior to inclusion. This study is approved by the ethics committee of the University of Potsdam (reference number 34/2012), Germany, and will be conducted according to the ethical standards of the Helsinki Declaration.

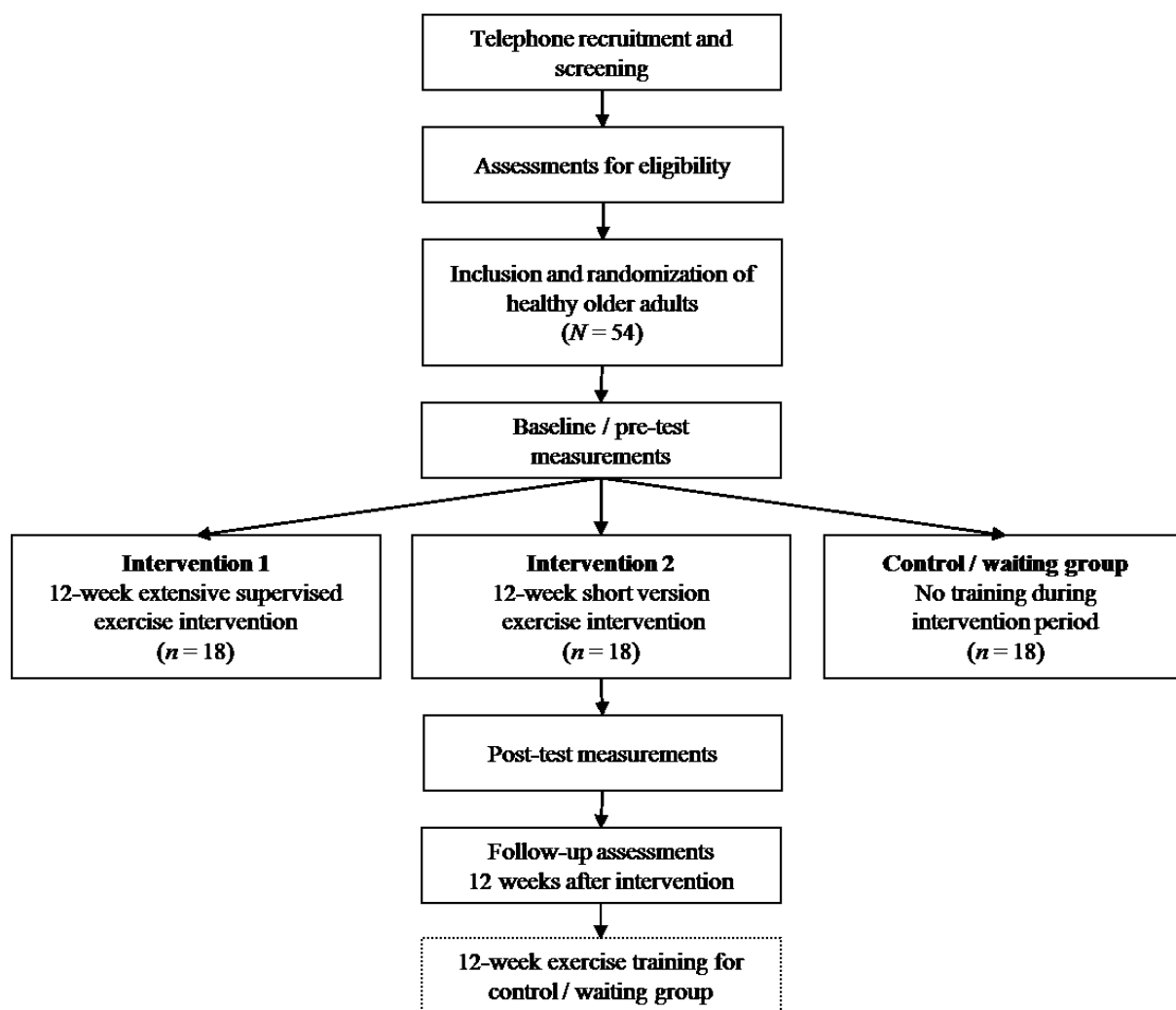
### *Questionnaires*

#### *Clock drawing test (CDT)*

The CDT will be used for cognitive screening (Mainland, Amodeo, & Shulman, 2013). Participants will be asked to “Please draw a clock and write all the numbers and hands” on a pre-drawn circle of 10 cm in diameter. Afterwards they will be instructed to “Write down the time your clock shows as if it were in a schedule for trains or in a TV guide”. The CDT will be graded pathological if any mistakes in writing the numbers and hands, or writing down the time occur. Inter-rater reliability was shown to be high (IRR = 0.91) (Thalman et al., 2002).

#### *Falls efficacy scale - International version (FES-I)*

Falls self-efficacy will be measured using the German 16-item FES-I (Dias et al., 2006). This questionnaire measures the level of concern about falling during social and physical activities indoors and outdoors on a 4-point Likert scale (1 = not at all concerned to 4 = very concerned). Internal validity (Cronbach’s alpha = 0.96) and test-retest reliability (ICC = 0.96) have been shown to be excellent (Yardley et al., 2005). Additionally, a 12-months fall history will be collected at baseline.



**Figure 1:** Flow chart of the study design.

#### *World health organization quality of life assessment-bref (WHOQOL-Bref)*

Quality of life and general health will be assessed by 26 items on a 5-point Likert scale in four domains: physical health, psychological health, social relationship and environment (Aigner et al., 2006). Scores for the WHOQOL-Bref range from 0-100 with a higher score indicating better quality of life. For this study, the German version of the WHOQOL-Bref will be applied (Angermeyer, Kilian, & Matschinger, 2000). The WHOQOL-Bref performs according to international standards in terms of reliability, validity, test-retest, and sensitivity to change analyses (Skevington, Sartorius, Amir, & Whoqol-Group, 2004).

#### *Freiburg questionnaire of physical activity (FQoPA)*

For the assessment of health-related physical activity, exercise, and estimation of energy expenditure we will apply the FQoPA (Frey & Berg, 2002). Participants will be asked to report

the amount of time spent in different activities during the past 7 days (everyday activities) and past month (sport and recreational activities). Energy requirements (MET) for physical activities are provided with the FQoPA allowing calculation of total weekly energy expenditure (< 15 MET\*h/week = “not active enough”, 15-30 MET\*h/week = “meets basic public health recommendations for physical activity”, > 30 MET\*h/week = “satisfactory active”) (Frey & Berg, 2002). The FQoPA has shown high test-retest reliability after 14 days and 6 months (Frey et al., 1999). Validity of the FQoPA has been shown by correlating physical activity data with maximum oxygen uptake ( $r = 0.422$ ) (Frey et al., 1999).

### *Tuning Fork Test*

A graduated Rydel-Seiffer tuning fork (Martin, Tuttlingen, Germany) will be used for testing vibration intensity at the internal malleolus of the dominant leg. The participants will be instructed to lie at ease in a supine position in a quiet, comfortably warm room. The tuning fork will be applied as perpendicular as possible resting on its own weight with the arms of the fork swinging maximally. Once the two arms are swinging, the fork vibrates at 64 Hz. Triangles with an arbitrary scale on calibrated weights at the extremities of the arms allow assessment of vibration threshold. When the participant indicates that vibration is no longer perceived, the point of intersection on the arbitrary scale (0 minimum to 8 maximum) is read. The readings of three repeated tests will be averaged and considered the vibration threshold. Pestronk et al. (2004) were able to show that the Rydel-Seiffer tuning fork has high inter- and intrarater reliability.

### *Balance and strength/power assessment*

The primary outcome measures will be balance and strength/power at baseline (pre-test), after the intervention (post-test) and 12 weeks after the intervention (follow-up). In general, balance assessment will be performed before strength/power assessment to reduce interfering effects of muscle fatigue (Granacher, Muehlbauer, Gschwind, Pfenninger, & Kressig, 2013).

### *Balance assessment and gait analysis*

Static steady-state balance will be assessed using the Romberg Test and Sharpened Romberg Test (Starischka, Dörning, Hagedorn, Sieber, & Schmidt, 1991) while standing on a force platform (Leonardo 105 Mechanograph<sup>®</sup>, Novotec Medical GmbH, Pforzheim, Germany; measurement error:  $\leq 0.2$  %). Participants will have to perform 4 tasks with increasing level

of difficulty: (1) standing in an upright position with feet closed and eyes open for 10 s without swaying while holding both arms extended to the front with palms facing upwards; (2) ditto, but with eyes closed; (3) ditto, but eyes open and feet in tandem stand; (4) ditto, but eyes closed and feet in tandem stand. Centre of pressure (CoP) displacements in mediolateral ( $CoP_{ml_s}$  in mm) and anterior-posterior ( $CoP_{ap_s}$  in mm) directions as well as standing time during the different test conditions will be assessed. Test termination criteria are displacing feet, lowering arms or opening eyes. Besides CoP displacements, stand time will be recorded using a stopwatch to nearest 0.01 s. Age-specific corresponding norm values are 14 s to 15 s (female) and 14.3 s to 17.5 s (male) (Starischka et al., 1991). For the Romberg Test (eyes open, ICC = 0.86 and eyes closed, ICC = 0.84) and Sharpened Romberg Test (eyes open, ICC = 0.70 and eyes closed, ICC = 0.91) high test-retest reliability has been shown (Steffen & Seney, 2008).

Dynamic steady-state balance will be tested while walking on an instrumented 10-m walkway using a two-dimensional OptoGait<sup>®</sup>-System (Bolzano, Italy). Participants will walk with their own footwear at self-selected speeds, initiating and terminating each walk a minimum of 2 m before and after the 10-m walkway to allow sufficient distance to accelerate to and decelerate from a steady-state of ambulation across the walkway. The rectangular OptoGait<sup>®</sup>-System is an opto-electrical measurement system consisting of transmitting and receiving bars for obtaining a two-dimensional measurement area. Each bar is 1 m in length and contains 100 LEDs that transmit continuously to each other. With a continuous connection between the two bars, any break in the connection can be measured and timed. The walking pattern will be monitored at 1,000 Hz, enabling spatial and temporal gait data to be collected. The OptoGait<sup>®</sup>-System demonstrated high discriminant and concurrent validity with a validated electronic walkway (GAITRite<sup>®</sup>-System) for the assessment of spatio-temporal gait parameters in orthopedic patients and healthy controls (Lienhard, Schneider, & Maffioletti, 2013). Hausdorff et al. (1997) reported that spatio-temporal parameters of gait are important mobility markers in community-dwelling older adults. Thus, means and standard deviations (SD) of stride time, stride length, stride velocity, and stride width will be computed. In addition, coefficients of variation (CV) for stride time, stride length, stride velocity, and stride width will be calculated according to the following formula:  $[CV = (SD / \text{mean}) \times 100]$  (Beauchet, Dubost, Aminian, Gonthier, & Kressig, 2005). Of note, the CV is a sensitive and clinically relevant marker for increased fall risk (Hausdorff, 2005). Further, it has been reported that gait velocity below 70 cm/s is associated with an increased risk of falling in old community-dwelling

adults (Montero-Odasso et al., 2005). Thus, using a stopwatch to the nearest 0.01 s, gait velocity will be assessed as a marker of fall risk. Granacher, Bridenbaugh, Muehlbauer, Wehrle, and Kressig (2011) recently reported that intraclass correlation coefficient (ICC) values for the above reported gait parameters were above 0.75. To resemble real life situations, static and dynamic steady-state balance will be tested under single (standing/walking) and dual task (standing/walking while counting backwards aloud) conditions. The cognitive interference task will comprise an arithmetic task, in which the participants recite out loud serial subtractions by three starting from a randomly selected number between 300 and 900 given by the experimenter (Pellecchia, 2005).

Proactive balance will be assessed using the Functional Reach Test (FRT) (Duncan, Weiner, Chandler, & Studenski, 1990) and the Timed up and Go Test (TUG) (Podsiadlo & Richardson, 1991). The FRT measures the maximal distance one can reach forward beyond arm's length while maintaining a fixed base of support in the standing position. Maximal reach distance of the right and left arm will be recorded, whereas a distance between 15.4 cm to 25.4 cm indicates a moderate risk for falls (Duncan et al., 1990). The FRT will be measured while standing on a force platform (Leonardo 105 Mechanograph<sup>®</sup>) which additionally allows collection of CoP displacements. The FRT showed excellent test-retest reliability (ICC = 0.92) in older adults (Duncan et al., 1990). Validity of the FRT has been proved by Newton (2001) when testing healthy community-dwelling older adults.

The TUG will be applied as described by Podsiadlo and Richardson (1991). Participants will be asked to perform the TUG at their self-selected habitual speed. One practice and one test trial will be performed. Time will be recorded with a stopwatch to the nearest 0.01 s. Before testing, a trained evaluator will provide standardized verbal instructions regarding the test procedures. Participants will be seated and instructed to walk 3 m, turn around, walk back to the chair and sit down. The stopwatch will be started on the command "ready-set-go" and stopped as the participant sits down. The TUG showed excellent test-retest reliability (ICC = 0.99) in older adults (Podsiadlo & Richardson, 1991).

During the reactive balance test, participants will stand in bipedal step stance on a two-dimensional balance platform (Posturomed, Haider Bioswing, Pullenreuth, Germany). The platform is mounted to four springs and is free to move in the transversal, anterior-posterior (ap), and mediolateral (ml) directions. The maximal natural frequency of the Posturomed is below 3 Hz. The mechanical constraints and the reliability of the system were described earlier (Mueller et al., 2004). If the platform is in neutral position, the maximum range of motion



in the ap and ml directions amounts to 70 mm, respectively. Mediolateral perturbation impulses will be applied in order to investigate reactive postural control of the participants. Therefore, the platform will be moved 2.5 cm from the neutral position in the ml direction, where it will be magnetically fixed. For experimental testing, participants will be asked to stand (i.e., bipedal step stance) in erect position with hands placed on hips and gaze fixated on a cross on the nearby wall. Three to five trials help participants to get accustomed to the measuring device. After investigators visually control the position of the subjects, the ml perturbation impulse will unexpectedly be applied by detaching the magnet. The platform suddenly accelerates in the medial direction. The participants' task is to damp the oscillating platform by balancing on the Postuomed. Summed oscillations of the platform in ml (SOml\_r) and ap (SOap\_r) directions will be assessed by means of a joystick-like 2D potentiometer (Megatron, Munich, Germany) which is connected to the platform. The potentiometer measures the position of the platform in degree (°). The signal will be differentiated, rectified, and integrated over the 10 s test interval. Three trials will be performed. The best trial (least oscillations in ml direction) will be used for further analysis. Muehlbauer et al. (2012) reported ICC values of 0.69 for SOml\_r and 0.40 for SOap\_r.

As a corresponding clinical test for reactive balance, the Push and Release Test (PRT) will be conducted. The PRT rates the postural response to a sudden release of a participant pressing backward on an examiner's hands placed on a participant's back (Jacobs, Horak, van Tran, & Nutt, 2006). The participant is instructed to stand in a comfortable stance with his or her eyes open and push backward against the palm of the examiner's hands. After the examiner suddenly releases his or her hands, the participant is required to regain balance (backward stepping until a proper position is reached). During testing, the examiner will be responsible for safety of the participant. For rating purposes, the actual amount of steps to regain balance (not those to reorient the feet) will be measured (0 = 1 step, 1 = 2-3 small steps backwards with independent recovery, 2 =  $\geq$  4 steps with independent recovery, 3 = steps with assistance for recovery, 4 = fall or unable to stand without assistance). The PRT showed high test-retest reliability (ICC = 0.84) with a sensitivity of 89 % and a specificity of 85 %.

#### *Strength/power assessment*

Handgrip strength will be measured to the nearest kilogram of each participant's dominant hand using a Jamar hand dynamometer (Sammons Preston Inc., Bolingbrook, USA) (Peolsson, Hedlund, & Oberg, 2001). The dominant hand will be determined according to the lateral

preference inventory (Coren, 1993). The measurements will be performed with participants sitting in an upright position and with the arm of the measured hand unsupported and parallel to the body. The width of the dynamometer's handle will be adjusted to each participant's hand size so that the middle phalanges rested on the inner handle. We will instruct participants to exert maximal force. Starting with one submaximal trial to get accustomed to the testing procedure, participants will perform one maximal test trial. The intraclass correlation coefficient was calculated for handgrip strength (ICC = 0.99) (Muehlbauer, Stuerchler, & Granacher, 2012). Additionally, the Jamar hand dynamometer has been shown to have acceptable concurrent validity in young and adults (Mathiowetz, 2002).

Lower extremity strength/power will be assessed by the Chair Stand Test using a force platform (Leonardo 105 Mechanograph<sup>®</sup>) (Whitney et al., 2005; Csuka & McCarty, 1985). The Chair Stand Test will be performed as a clinical test, where participants will sit on a chair with their arms crossed on their chest, and stand up and sit down 5 times as quickly as they can. Time measured by a stop watch to the nearest 0.01 s indicates insufficient ( $\geq 16.7$  s), sufficient (13.7 s to 16.6 s), good (11.2 s to 13.6 s), and very good strength performance ( $\leq 11.1$  s) (Whitney et al., 2005). For the Chair Stand Test, high test-retest reliability has been shown (ICC = 0.89) (Tiedemann, Shimada, Sherrington, Murray, & Lord, 2008).

Participants will additionally perform maximal vertical countermovement jumps while standing on a force platform (Leonardo 105 Mechanograph<sup>®</sup>). The vertical ground reaction force will be sampled at 1,000 Hz. During the countermovement jumps, subjects stand in an upright position on the force plate and will be instructed to begin the jump with a downward movement, which will be immediately followed by a concentric upward movement, resulting in a maximal vertical jump. Subjects will perform three countermovement jumps with a resting period of 1 minute between jumps. For each of these trials, subjects will be asked to jump as high as possible. The best trial in terms of maximal jump height will be taken for further data analysis. In a study by Granacher et al. (2012) intraclass correlation coefficient was calculated for countermovement jumps power and amounted to ICC = 0.81.

The Stair Climb Power Test (SCP) will be used as a clinical equivalent for the countermovement jumps (Bean, Kiely, LaRose, Alian, & Frontera, 2007). Participants will be instructed to safely ascend a 10-stair flight (each stair height 16.5 cm) as fast as possible. Use of the hand-rail will be allowed for safety reasons only. Timing begins after the countdown "ready-set-go" on the word "go" and stops when both of the participant's feet reaches the top step. Time will be measured by a stopwatch to the nearest 0.01 s and the average of 2 trials will be taken. SCP

will be calculated by the formula: [power = force x velocity]. Test-retest reliability has been recorded and proved to be excellent ( $r = 0.99$ ) (Bean et al., 2007).

#### *Assessment of body composition*

A non-invasive bioelectrical impedance analysis (BIA) will be conducted before balance and strength/power assessments to minimize the effect of hydration status on measurements. Participants will be instructed to abstain from caffeine and alcohol 24 h, and exercise 12 h prior to testing according to published guidelines for BIA (Shafer, Siders, Johnson, & Lukaski, 2009). For BIA an octopolar tactile-electrode impedance meter (InBody 720, BioSpace, Seoul, Korea) will be used to estimate body composition according to the manufacturer's guidelines. Multiple frequencies at 5, 50, 250 and 500 kHz will be used to measure intracellular and extracellular water separately. The participants will be measured under laboratory conditions standing barefoot on the device. With abducted arms 15° and legs 45° apart, they will hold a hand electrode with contact of all 10 fingers while the heels and forefeet will be placed appropriately on the foot electrode. Then an alternating current of 250 mA of intensity will be applied to measure impedance of arm, trunk, and leg muscles. Whole-body resistance will be calculated as the sum of segmental resistance (right arm + left arm + trunk + right leg + left leg). The BIA with InBody 720 has been validated by dual-energy X-ray absorptiometry ( $r^2 = 0.93$ ) (Lim et al., 2009). In normal and overweight adults multiple frequency BIA underestimated percentage of body fat within the precision of the BIA instrument (2 %) (Lim et al., 2009; Shafer et al., 2009).

#### *Design of exercise interventions*

Study participants will be randomized ([www.randomizer.org](http://www.randomizer.org)) with a gender ratio of 1:1 into 2 intervention groups (INT1 and INT2) and a control/waiting group (CG). The first intervention group (INT1) will conduct a 12-week exercise program according to the practice guide developed by the expert panel. The program consists of task-specific exercises for (1) static steady-state balance, (2) dynamic steady-state balance, (3) proactive balance, (4) reactive balance, and (5) strength as well as (6) power, especially for the lower extremities and the trunk muscles. Exercises will be performed 3 times per week on non-consecutive days, twice supervised for 45 min (incl. 15 min for warm-up and cool-down), and once at home for 30 min individually. The second intervention group (INT2) follows the same exercise routine as the first in-

tervention group (INT1), except that they perform a short version of the program called ‘3 times 3’. After a supervised introduction into the ‘3 times 3’ program, INT2 will individually train at home 3 times per week for 30 min. Each ‘3 times 3’ training session will consist of only one exercise within the 3 domains (static balance, dynamic balance, and strength). Quality and quantity of exercises will be controlled by weekly phone calls and a training log book. The control/waiting group will not participate in any form of training during the experimental period, but will receive the extensive supervised program after the experimental period. Pre and post assessment of all variables for all groups (INT1, INT2, and CG) will be performed before and after the 12-week intervention period. Follow-up measurements 12 weeks after the intervention cessation will allow the assessment of detraining effects. Duration of a single assessment amounts to 90 min per participant.

### *Intervention program*

The expert panel selected balance and strength/power exercises which can be performed with one’s own bodyweight or with the help of small, low-cost exercise equipment (i.e., small weights, resistance bands, unstable surfaces). However, intensity control for strength/power exercises performed with one’s own bodyweight is more complicated compared to when using resistance training machines. In this study, intensity during training will be regulated using the Borg rating of perceived exertion scale (i.e., 6-20 points, maximal exertion at 20 points) (Borg, 1970). According to the individual fitness level, exercises should be performed with a perceived exertion between 10 and 16 points (light to hard) during balance and resistance/power training. Exercise intensity will be progressed individually using the Borg Rating of Perceived Exertion scale and varying the balance and strength/power exercises in order to sufficiently stimulate the neuromuscular system (Muehlbauer, Roth, Bopp, & Granacher, 2012). Rate of perceived exertion will be adjusted every 2 weeks by the therapist (INT1) or via phone calls (INT2). Strength/power exercises will be progressed from single to multiple joint, isometric to dynamic muscle contraction, short to long lever arm and slow to fast exercises (Granacher, Lacroix, Muehlbauer, Roettger, & Gollhofer, 2013). Further details regarding the contents of the intervention program are described in Tables 1 and 2 for resistance/power training, and Tables 3 and 4 for static and dynamic steady-state, proactive, and reactive balance training (see also Figures 2, 3, and 4).

**Table 1:** Guidelines for heavy resistance training.

<b>Exercise variables</b>	<b>Recommendations</b>
Intensity	Defined by level of difficulty, fatigue and number of repetitions  Beginner: 12-13 RPE (somewhat hard)  Advanced: 14-16 RPE (hard)
Quality	Technically correct movement  Maximal range of motion
Speed of movement, contraction velocity	2 s concentric muscle contraction, 2 s eccentric muscle contraction (ratio 1:1)
Sets	2-3 (at home 3 sets)
Frequency	2 group sessions per week and 1 session alone at home (alternating resistance and balance training)
Repetitions	Beginner: 10-15 (moderate resistance until muscle fatigue)  Advanced: 8-12 (high resistance until muscle fatigue)
Rest	2 min. between sets

*RPE* = rate of perceived exertion

**Table 2:** Guidelines for muscle power training.

<b>Exercise variables</b>	<b>Recommendations</b>
Intensity	Defined by level of difficulty, fatigue and number of repetitions  10-13 RPE (light to somewhat hard)
Quality	Technically correct movement  Maximal range of motion
Speed of movement, contraction velocity	Concentric contraction as fast as possible  Approx. 1 s concentric muscle contraction, approx. 2 s eccentric muscle contraction (ratio 1:2)
Sets	2-3 (at home 3 sets)
Frequency	2 group sessions per week and 1 session alone at home (alternating resistance and balance training)
Repetitions	8-10
Rest	2 min. between sets

*RPE* = rate of perceived exertion

**Table 3:** Guidelines for static steady-state, reactive, and proactive balance exercises.

<b>Balance (static)</b>	<b>Exercise variables</b>	<b>Recommendations</b>
Steady-state	Base of support	Stable to instable: bipedal - semi-tandem - tandem - one leg stance (Figure 2)
	Position of feet	i.e., lateral or medial weight shift, on heels or toes, toe angle in or out
	Surface	i.e., from soft to hard (e.g., grass to concrete), from stable to instable (e.g., concrete to sand)
	Sensory input	Impede vision or hearing
	Dual-/Multi-tasking	Additional motor task - additional cognitive task - additional motor and cognitive tasks
	Speed of movement	Decrease or increase of execution speed (i.e. upper arm movements)
	Equipment	Use of i.e., free weights, elastic bands, balls
Reactive	Controlled perturbations applied by therapist	Reaction to external thread (push or pull) varying in speed, amplitude and direction on ankle, hip, trunk or shoulder level
Proactive	ADL	Combination of steady-state (static) balance tasks with mobility in daily life (e.g., standing up from a chair while reciting a poem and holding a cup of water)

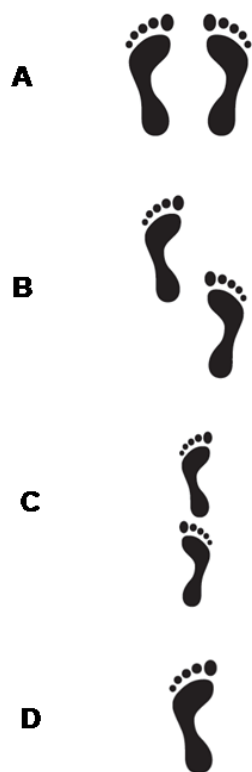
*ADL* = activities of daily living

**Table 4:** Guidelines for dynamic steady-state, reactive, and proactive balance exercises.

<b>Balance (dynamic)</b>	<b>Exercise variables</b>	<b>Recommendations</b>
Steady-state	Base of support	Stable to instable: normal gait - narrow gait – overlapping gait - tandem gait (Figure 3)
	Position of feet	i.e., lateral or medial weight shift, on heels or toes, toe angle in or out
	Surface	i.e., from soft to hard (e.g., grass to concrete), from stable to instable (e.g., concrete to sand)
	Sensory input	Impede vision or hearing
	Dual-/Multi-tasking	Additional motor task - additional cognitive task - additional motor and cognitive tasks
	Speed of movement	Decrease or increase of execution speed (i.e. walking speed)
	Equipment	Use of i.e., free weights, elastic bands, balls
	Direction	Forwards - backwards - to the left or right - diagonal
	Rhythm	Slow - fast - intermittent slow and fast
Reactive	Controlled perturbations applied by therapist	Reaction to external thread (push or pull) varying in speed, amplitude and direction on ankle, hip, trunk or shoulder level
Proactive	ADL	Combination of steady-state (dynamic) balance tasks with mobility in daily life (e.g., walking upstairs backwards while counting backwards aloud from 50 minus 2)

*ADL* = activities of daily living





**Figure 2:** Base of support during static steady-state balance. (A) bipedal stance, (B) semi-tandem stance, (C) tandem stance, (D) monopodal stance.



### *Statistics and sample size*

An a priori power analysis was conducted to detect the sample size that is necessary to find statistically significant exercise effects (Faul, Erdfelder, Lang, & Buchner, 2007) based on a study assessing the effects of balance training on postural control in older adults (Granacher, Wick et al., 2011). Considering a dropout rate of 10 %, 18 participants per arm will be required to achieve 90 % power (type II error of 0.10) with a type I error of 5 %. Data will be analyzed using a 2- and 3-way repeated measures analysis of variance (ANOVA) consisting of groups (INT1, INT2, CG) and time (pre-test, post-test, follow-up). Bonferroni post-hoc test will be used for statically significant ( $p < 0.05$ ) group and time differences. Associations between clinical and biomechanical tests will be reported by their correlation coefficient ( $r$  value), level of significance ( $p$  value) and the amount of variance explained ( $r^2$  value). Values of  $r = 0.10$  indicate a small,  $r = 0.30$  a medium and  $r = 0.50$  a large-size correlation [i.e. effect size (ES)] (Cohen, 1992).

### **Discussion**

The nationwide implementation of effective fall prevention exercise programs in industrial countries is limited. The present trial applies and evaluates a public practice guide for balance and resistance training that may provide a feasible, safe, and effective approach for fall prevention in older adults. In contrast to an epidemiological approach, in this trial, we will conduct an intervention based on three major intrinsic fall risk factors (balance impairments, gait instabilities, and muscle weakness). This will allow the use of several extensive clinical and biomechanical measurement tools for evaluation purposes. The proposed exercises require relatively low supervision and material costs, and offer practical information in terms of training volume, (i.e., type, frequency, duration) and intensity. A major advantage of this intervention compared to earlier fall prevention exercise programs is its broad and cost-free applicability and sustainability for German and French speaking older adults.

The expected effect of our fall prevention exercise program is based on a large recent meta-analysis by Gillespie et al. (2012) who showed that multiple-component group exercise and home-based exercise reduce the rate of falls and fall risk (rate ratio 0.71, 95 % CI 0.63 to 0.82 and risk ratio 0.85, 95 % CI 0.76 to 0.96 vs. rate ratio 0.68, 95 % CI 0.58 to 0.80 and risk ratio 0.78, 95 % CI 0.64 to 0.94). Previous studies showed that combined balance and resistance training may positively affect physical (i.e., balance and strength), mental (i.e., quality of life and fear of falling), and functional performance (i.e., ADL) (Granacher et al., 2010; Gra-

nacher, Gollhofer, & Strass, 2006; Granacher, Gruber, & Gollhofer, 2009a; Granacher, Gruber, & Gollhofer, 2009b; Granacher, Wick et al., 2011). Uncertainty remains if resistance training alone is sufficient to prevent falls in older adults (Latham, Bennett, Stretton, & Anderson, 2004). Recent studies reported that especially muscle power exercises with lower loads and faster movement velocities improve ADL and therefore may be superior compared to traditional progressive resistance training (Granacher, Muehlbauer, Zahner et al., 2011; Hazell, Kenno, & Jakobi, 2007; Henwood, Riek, & Taaffe, 2008; Henwood & Taaffe, 2005; Latham et al., 2003; Latham et al., 2004). In contrast, balance exercises are recommended for all older adults who had a fall (Moreland et al., 2003), however, there is hardly any evidence about training load, volume, and frequency (Granacher, Muehlbauer, Zahner et al., 2011).

The current trial will add valuable information to the knowledge of effects of supervision and dose-response-relations for exercise in older adults. Particularly the use of two different intervention arms (supervised group exercise program vs. unsupervised home-based exercise program) will give some indication of the effects of supervision and the minimal amount of exercise needed to stimulate physical performance adaptations. If the short version of the program (3 times per week for 30 min) will prove to be effective, this may lower the barrier for sedentary older adults to take up exercising. If intrinsic fall risk factors can be positively influenced by our proposed intervention regime, future trials will need to investigate any possible effect on fall rate in older adults. Additionally, in this trial, each clinical test will be compared to a gold-standard instrumented test. This cross-validation may facilitate the implementation of easy-to-administer balance and strength/power assessments into practice. Regular simple balance and strength/power assessments are important for training prescription and performance regarding exercise variation and progression. Furthermore, measuring gait velocity, grip strength and muscle mass will allow diagnosis of sarcopenia according to EWGSOP criteria, and may add knowledge to sensitivity and specificity of strength/power test to this important geriatric syndrome.

In summary, this trial will provide insight into the effect of fall prevention exercise applicable for a broad population and setting, both in community and sporting groups and at home. Practitioners, exercise therapists, and instructors will be provided with a feasible, validated exercise routine whose effect on intrinsic fall risk factors is scientifically evaluated. Furthermore, older adults who participate in the present program represent possible multipliers for a broader acceptance of important exercise and health-enhancing measures. Finally, the results of the

current trial may help to further develop theories and models explaining balance and resistance training effects in general and particularly in older adults.

## References

- Aigner, M., Forster-Streffleur, S., Prause, W., Freidl, M., Weiss M., & Bach M. (2006). What does the WHOQOL-Bref measure? Measurement overlap between quality of life and depressive symptomatology in chronic somatoform pain disorder. *Social Psychiatry and Psychiatric Epidemiology*, *41*(1):81-86. doi: 10.1007/s00127-005-0997-8
- American Geriatrics Society, British Geriatrics Society, American Academy of Orthopaedic Surgeons Panel on Falls Prevention (2001). Guideline for the prevention of falls in older persons. *Journal of the American Geriatrics Society*, *49*(5):664-672.
- Angermeyer, M. C., Kilian, R., Matschinger, H. (2000). *WHOQOL-100 und WHOQOL-Bref Handbuch für die deutschsprachige Version der WHO-Instrumente zur Erfassung von Lebensqualität*. Göttingen: Hogrefe.
- Axer, H., Axer, M., Sauer, H., Witte, O. W., Hagemann, G. (2010). Falls and gait disorders in geriatric neurology. *Clinical Neurology and Neurosurgery*, *112*(4):265-274. doi: 10.1016/j.clineuro.2009.12.015
- Bean, J. F., Kiely, D. K., LaRose, S., Alian, J., & Frontera, W. R. (2007). Is stair climb power a clinically relevant measure of leg power impairments in at-risk older adults? *Archives of Physical Medicine & Rehabilitation*, *88*(5), 604–609. <https://doi.org/10.1016/j.apmr.2007.02.004>
- Beauchet, O., Dubost, V., Aminian, K., Gonthier, R., & Kressig, R. W. (2005). Dual-task-related gait changes in the elderly: Does the type of cognitive task matter? *Journal of Motor Behavior*, *37*(4), 259–264.
- Bloch, F., Thibaud, M., Tournoux-Facon, C., Brèque, C., Rigaud, A.-S., Dugué, B., & Kemoun, G. (2013). Estimation of the risk factors for falls in the elderly: Can meta-analysis provide a valid answer? *Geriatrics & Gerontology International*, *13*(2), 250–263. <https://doi.org/10.1111/j.1447-0594.2012.00965.x>
- Borg, G. (1970). Perceived exertion as an indicator of somatic stress. *Scandinavian Journal of Rehabilitation Medicine*, *2*(2), 92–98.
- Brewer, L. M., Kelly, R., Donegan, C., Moore, A. R., & Williams, D. (2011). Poor return of functional mobility after hip fracture in older patients-it's time to improve on hip fracture prevention. *Journal of the American Geriatrics Society*, *59*(8), 1562–1563. <https://doi.org/10.1111/j.1532-5415.2011.03535.x>
- Carmeli, E., Coleman, R., & Reznick, A. Z. (2002). The biochemistry of aging muscle. *Experimental Gerontology*, *37*(4), 477–489.
- Ceglia, L. (2009). Vitamin D and its role in skeletal muscle. *Current Opinion in Clinical Nutrition and Metabolic Care*, *12*(6), 628–633. <https://doi.org/10.1097/MCO.0b013e328331c707>
- Clark, B. C., & Manini, T. M. (2008). Sarcopenia =/= dynapenia. *Journals of Gerontology. Series A-Biological Sciences and Medical Sciences*, *63*(8), 829–834.
- Cohen, J. (1992). A power primer. *Psychological bulletin*, *112*(1), 155–159.
- Coren, S. (1993). The lateral preference inventory for measurement of handedness, footedness, eyedness, and earedness: Norms for young adults. *Bulletin of the Psychonomic Society*, *31*(1), 1–3. <https://doi.org/10.3758/BF03334122>

- Cruz-Jentoft, A. J., Baeyens, J. P., Bauer, J. M., Boirie, Y., Cederholm, T., Landi, F., . . . Zamboni, M. (2010). Sarcopenia: European consensus on definition and diagnosis: Report of the European Working Group on Sarcopenia in Older People. *Age and Ageing, 39*(4), 412–423. <https://doi.org/10.1093/ageing/afq034>
- Csuka, M., & McCarty, D. J. (1985). Simple method for measurement of lower extremity muscle strength. *The American Journal of Medicine, 78*(1), 77–81.
- Day, L. M. (2013). Fall prevention programs for community-dwelling older people should primarily target a multifactorial intervention rather than exercise as a single intervention. *Journal of the American Geriatrics Society, 61*, 284-5; discussion 285-6. [https://doi.org/10.1111/jgs.12095\\_3](https://doi.org/10.1111/jgs.12095_3)
- Dias, N., Kempen, G. I. J. M., Todd, C. J., Beyer, N., Freiburger, E., Piot-Ziegler, C., . . . Hauer, K. (2006). [The German version of the Falls Efficacy Scale-International Version (FES-I)]. *Zeitschrift für Gerontologie und Geriatrie, 39*(4), 297–300. <https://doi.org/10.1007/s00391-006-0400-8>
- Duncan, P. W., Studenski, S., Chandler, J., & Prescott, B. (1992). Functional reach: Predictive validity in a sample of elderly male veterans. *Journal of gerontology, 47*(3), M93-8.
- Duncan, P. W., Weiner, D. K., Chandler, J., & Studenski, S. (1990). Functional reach: A new clinical measure of balance. *Journals of Gerontology, 45*(6), M192-7.
- Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G\*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191.
- Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). “Mini-mental state”. A practical method for grading the cognitive state of patients for the clinician. *Journal of psychiatric research, 12*(3), 189–198.
- Franklin, R. C., Boehm, J., King, J., Newitt, R., Grant, T., Kurkowsky, B., . . . Lloyd, J. (2013). A framework for the assessment of community exercise programmes: A tool to assist in modifying programmes to help reduce falls risk factors. *Age and Ageing, 42*(4), 536–540. <https://doi.org/10.1093/ageing/aft060>
- Frey, I., Berg, A., Grathwohl, D., & Keul, J. (1999). [Freiburg Questionnaire of physical activity—development, evaluation and application]. *Sozial- und Präventivmedizin, 44*(2), 55–64.
- Frey, I., & Berg, A. (2010). Physical activity counseling: Assessment of physical activity by questionnaire. *European Journal of Sport Science, 2*(4), 1–6. <https://doi.org/10.1080/17461390200072406>
- Gillespie, L. D., Robertson, M. C., Gillespie, W. J., Sherrington, C., Gates, S., Clemson, L. M., & Lamb, S. E. (2012). Interventions for preventing falls in older people living in the community. *The Cochrane Database of Systematic Reviews, 9*, Cd007146. <https://doi.org/10.1002/14651858.CD007146.pub3>
- Gostynski, M., Ajdacic-Gross, V., Gutzwiller, F., Michel, J. P., & Herrmann, F. (1999). [Epidemiological analysis of accidental falls by the elderly in Zurich and Geneva]. *Schweizerische medizinische Wochenschrift, 129*(7), 270–275.
- Granacher, U., Gollhofer, A., Hortobagyi, T., Kressig, R. W., & Muehlbauer, T. (2013). The importance of trunk muscle strength for balance, functional performance, and fall prevention in seniors: a systematic review. *Sports Medicine, 43*(7), 627–641. <https://doi.org/10.1007/s40279-013-0041-1>
- Granacher, U., Gollhofer, A., & Strass, D. (2006). Training induced adaptations in characteristics of postural reflexes in elderly men. *Gait & Posture, 24*(4), 459–466. <https://doi.org/10.1016/j.gaitpost.2005.12.007>

- Granacher, U., Gruber, M., & Gollhofer, A. (2009a). Resistance training and neuromuscular performance in seniors. *International Journal of Sports Medicine*, *30*(9), 652–657. <https://doi.org/10.1055/s-0029-1224178>
- Granacher, U., Gruber, M., & Gollhofer, A. (2009b). [The impact of sensorimotor training on postural control in elderly men]. *Deutsche Zeitschrift für Sportmedizin*, *60*(12), 387–393.
- Granacher, U., Lacroix, A., Muehlbauer, T., Roettger, K., & Gollhofer, A. (2013). Effects of core instability strength training on trunk muscle strength, spinal mobility, dynamic balance and functional mobility in older adults. *Gerontology*, *59*(2), 105–113. <https://doi.org/10.1159/000343152>
- Granacher, U., Muehlbauer, T., Bridenbaugh, S., Bleiker, E., Wehrle, A., & Kressig, R. W. (2010). Balance training and multi-task performance in seniors. *International Journal of Sports Medicine*, *31*(5), 353–358. <https://doi.org/10.1055/s-0030-1248322>
- Granacher, U., Muehlbauer, T., Bridenbaugh, S. A., Wolf, M., Roth, R., Gschwind, Y., . . . Kressig, R. W. (2012). Effects of a salsa dance training on balance and strength performance in older adults. *Gerontology*, *58*(4), 305–312. <https://doi.org/10.1159/000334814>
- Granacher, U., Muehlbauer, T., Gollhofer, A., Kressig, R. W., & Zahner, L. (2011). An intergenerational approach in the promotion of balance and strength for fall prevention - a mini-review. *Gerontology*, *57*(4), 304–315. <https://doi.org/10.1159/000320250>
- Granacher, U., Muehlbauer, T., Gschwind, Y. J., Pfenninger, B., & Kressig, R. W. (2013). Bedeutung von Kraft und Gleichgewicht für die Sturzrisikodiagnostik und Sturzprävention im Alter. *Zeitschrift für Gerontologie und Geriatrie* [Epub ahead of print].
- Granacher, U., Muehlbauer, T., Zahner, L., Gollhofer, A., & Kressig, R. W. (2011). Comparison of traditional and recent approaches in the promotion of balance and strength in older adults. *Sports Medicine*, *41*(5), 377–400. <https://doi.org/10.2165/11539920-000000000-00000>
- Granacher, U., Wick, C., Rueck, N., Esposito, C., Roth, R., & Zahner, L. (2011). Promoting balance and strength in the middle-aged workforce. *International Journal of Sports Medicine*, *32*(1), 35–44. <https://doi.org/10.1055/s-0030-1267214>
- Granacher, U., Bridenbaugh, S. A., Muehlbauer, T., Wehrle, A., & Kressig, R. W. (2011). Age-related effects on postural control under multi-task conditions. *Gerontology*, *57*(3), 247–255. <https://doi.org/10.1159/000322196>
- Granacher, U., Muehlbauer, T., & Gruber, M. (2012). A qualitative review of balance and strength performance in healthy older adults: Impact for testing and training. *Journal of aging research*, *2012*, 708905. <https://doi.org/10.1155/2012/708905>
- Greenberg, S. A. (2007). How to try this: The Geriatric Depression Scale: Short Form. *The American journal of nursing*, *107*(10), 60–9. <https://doi.org/10.1097/01.NAJ.0000292204.52313.f3>
- Gschwind, Y. J., Wolf, I., Bridenbaugh, S. A., & Kressig, R. W. (2011). Basis for a Swiss perspective on fall prevention in vulnerable older people. *Swiss Medical Weekly*, *141*, w13305. <https://doi.org/10.4414/smw.2011.13305>
- Haleem, S., Lutchman, L., Mayahi, R., Grice, J. E., & Parker, M. J. (2008). Mortality following hip fracture: Trends and geographical variations over the last 40 years. *Injury-International Journal of the Care of the Injured*, *39*(10), 1157–1163. <https://doi.org/10.1016/j.injury.2008.03.022>

- Hausdorff, J. M., Edelberg, H. K., Mitchell, S. L., Goldberger, A. L., & Wei, J. Y. (1997). Increased gait unsteadiness in community-dwelling elderly fallers. *Archives of Physical Medicine & Rehabilitation*, 78(3), 278–283.
- Hausdorff, J. M. (2005). Gait variability: Methods, modeling and meaning. *Journal of Neuroengineering and Rehabilitation*, 2, 19. <https://doi.org/10.1186/1743-0003-2-19>
- Hazell, T., Kenno, K., & Jakobi, J. (2007). Functional benefit of power training for older adults. *Journal of Aging and Physical Activity*, 15, 349–359.
- Henderson, G. C., Irving, B. A., & Nair, K. S. (2009). Potential application of essential amino Acid supplementation to treat sarcopenia in elderly people. *The Journal of Clinical Endocrinology and Metabolism*, 94(5), 1524–1526. <https://doi.org/10.1210/jc.2009-0458>
- Henwood, T. R., Riek, S., & Taaffe, D. R. (2008). Strength versus muscle power-specific resistance training in community-dwelling older adults. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 63(1), 83–91.
- Henwood, T. R., & Taaffe, D. R. (2005). Improved physical performance in older adults undertaking a short-term programme of high-velocity resistance training. *Gerontology*, 51(2), 108–115. <https://doi.org/10.1159/000082195>
- Howley, E. T., & Franks, B. D. (2003). *Health fitness instructor's handbook* (4<sup>th</sup> ed.). Champaign, IL: Human Kinetics.
- Jacobs, J. V., Horak, F. B., van Tran, K., & Nutt, J. G. (2006). An alternative clinical postural stability test for patients with Parkinson's disease. *Journal of neurology*, 253(11), 1404–1413. doi:10.1007/s00415-006-0224-x
- Koeneman, M. A., Verheijden, M. W., Chinapaw, M. J. M., & Hopman-Rock, M. (2011). Determinants of physical activity and exercise in healthy older adults: A systematic review. *International Journal of Behavioral Nutrition and Physical Activity*, 8, 142. <https://doi.org/10.1186/1479-5868-8-142>
- Krampe, R. T., Rapp, M. A., Bondar, A., & Baltes, P. B. (2003). [Allocation of cognitive resources during the simultaneous performance of cognitive and sensorimotor tasks]. *Der Nervenarzt*, 74(3), 211–218. <https://doi.org/10.1007/s00115-002-1325-0>
- Latham, N. K., Anderson, C. S., Lee, A., Bennett, D. A., Moseley, A., & Cameron, I. D. (2003). A randomized, controlled trial of quadriceps resistance exercise and vitamin D in frail older people: the Frailty Interventions Trial in Elderly Subjects (FITNESS). *Journal of the American Geriatrics Society*, 51(3), 291–299.
- Latham, N. K., Bennett, D. A., Stretton, C. M., & Anderson, C. S. (2004). Systematic review of progressive resistance strength training in older adults. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 59(1), 48–61.
- Lee, A. Y. J., Tan, J., Koh, J., Fook-Chong, S. M. C., Lo, N. N., & Howe, T. S. (2012). Five-year outcome of individuals with hip fracture admitted to a Singapore hospital: Quality of life and survival rates after treatment. *Journal of the American Geriatrics Society*, 60(5), 994–996. <https://doi.org/10.1111/j.1532-5415.2012.03936.x>
- Lienhard, K., Schneider, D., & Maffioletti, N. A. (2013). Validity of the Optogait photoelectric system for the assessment of spatiotemporal gait parameters. *Medical engineering & physics*, 35(4), 500–504. <https://doi.org/10.1016/j.medengphy.2012.06.015>



- Lim, J. S., Hwang, J. S., Lee, J. A., Kim, D. H., Park, K. D., Jeong, J. S., & Cheon, G. J. (2009). Cross-calibration of multi-frequency bioelectrical impedance analysis with eight-point tactile electrodes and dual-energy X-ray absorptiometry for assessment of body composition in healthy children aged 6-18 years. *Pediatrics international: official journal of the Japan Pediatric Society*, *51*(2), 263–268. <https://doi.org/10.1111/j.1442-200X.2008.02698.x>
- Little, R. M. D., Paterson, D. H., Humphreys, D. A., & Stathokostas, L. (2013). A 12-month incidence of exercise-related injuries in previously sedentary community-dwelling older adults following an exercise intervention. *BMJ open*, *3*(6). <https://doi.org/10.1136/bmjopen-2013-002831>
- Lopez, M. N., Charter, R. A., Mostafavi, B., Nibut, L. P., & Smith, W. E. (2005). Psychometric properties of the Folstein Mini-Mental State Examination. *Assessment*, *12*(2), 137–144. <https://doi.org/10.1177/1073191105275412>
- Lord, S. R., Sherrington, C., Cameron, I. D., & Close, J. C. T. (2011). Implementing falls prevention research into policy and practice in Australia: Past, present and future. *Journal of Safety Research*, *42*(6), 517–520. <https://doi.org/10.1016/j.jsr.2010.11.008>
- Lord, S. R., Sherrington, C., Menz, H. B., & Close, J. C. T. (2007). *Falls in Older People*. Cambridge: Cambridge University Press.
- Mainland, B. J., Amodeo, S., & Shulman K. I. (2013). *Multiple clock drawing scoring systems: simpler is better*. *International Journal of Geriatric Psychiatry*. [Epub ahead of print].
- Mathiowetz, V. (2002). Comparison of Rolyan and Jamar dynamometers for measuring grip strength. *Occupational therapy international*, *9*(3), 201–209.
- McCallum, J. (2011). Ageing research directions for Australia. *Australasian journal on ageing*, *30 Suppl 2*, 1–3. <https://doi.org/10.1111/j.1741-6612.2011.00566.x>
- Montero-Odasso, M., Schapira, M., Soriano, E. R., Varela, M., Kaplan, R., Camera, L. A., & Mayorga, L. M. (2005). Gait velocity as a single predictor of adverse events in healthy seniors aged 75 years and older. *Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *60*(10), 1304–1309.
- Moreland, J., Richardson, J., Chan, D. H., O'Neill, J., Bellissimo, A., Grum, R. M., & Shanks, L. (2003). Evidence-based guidelines for the secondary prevention of falls in older adults. *Gerontology*, *49*(2), 93–116.
- Muehlbauer, T., Besemer, C., Wehrle, A., Gollhofer, A., & Granacher, U. (2012). Relationship between strength, power and balance performance in seniors. *Gerontology*, *58*(6), 504–512. <https://doi.org/10.1159/000341614>
- Muehlbauer, T., Stuerchler, M., & Granacher, U. (2012). Effects of climbing on core strength and mobility in adults. *International Journal of Sports Medicine*, *33*(6), 445–451. <https://doi.org/10.1055/s-0031-1301312>
- Muehlbauer, T., Roth, R., Bopp, M., & Granacher, U. (2012). An exercise sequence for progression in balance training. *J Strength Cond Res*, *26*(2), 568–574. <https://doi.org/10.1519/JSC.0b013e318225f3c4>
- Muehlberg, W., & Sieber, C. (2004). Sarcopenia and frailty in geriatric patients: Implications for training and prevention. *Zeitschrift für Gerontologie und Geriatrie*, *37*(1), 2–8. <https://doi.org/10.1007/s00391-004-0203-8>
- Mueller, O., Günther, M., Krauss, I., & Horstmann, T. (2004). [Physical characterization of the therapeutic device Posturomed as a measuring device—presentation of a procedure to characterize balancing ability]. *Biomedizinische Technik. Biomedical engineering*, *49*(3), 56–60. <https://doi.org/10.1515/BMT.2004.011>

- Newton, R. A. (2001). Validity of the multi-directional reach test: A practical measure for limits of stability in older adults. *Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 56(4), M248-52.
- Orr, R., Vos, N. J. de, Singh, N. A., Ross, D. A., Stavrinou, T. M., & Fiatarone-Singh, M. A. (2006). Power training improves balance in healthy older adults. *Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 61(1), 78–85.
- Pellecchia, G. L. (2005). Dual-task training reduces impact of cognitive task on postural sway. *Journal of Motor Behavior*, 37(3), 239–246. <https://doi.org/10.3200/JMBR.37.3.239-246>
- Peolsson, A., Hedlund, R., & Oberg, B. (2001). Intra- and inter-tester reliability and reference values for hand strength. *Journal of Rehabilitation Medicine*, 33(1), 36–41.
- Pestronk, A., Florence, J., Levine, T., Al-Lozi, M. T., Lopate, G., Miller, T., . . . Stambuk, M. (2004). Sensory exam with a quantitative tuning fork: Rapid, sensitive and predictive of SNAP amplitude. *Neurology*, 62(3), 461–464.
- Podsiadlo, D., & Richardson, S. (1991). The timed “Up & Go”: A test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society*, 39(2), 142–148.
- Pretto, M., Spirig, R., Kaelin, R., Muri-John, V., Kressig, R. W., & Suhm, N. (2010). Outcomes of elderly hip fracture patients in the Swiss healthcare system: A survey prior to the implementation of DRGs and prior to the implementation of a Geriatric Fracture Centre. *Swiss Medical Weekly*, 140, w13086. <https://doi.org/10.4414/smw.2010.13086>
- Prevention of Falls Network Europe (ProFaNE). (2007). *Manual for Falls Prevention Classification System*. Retrieved from <http://www.profane.eu.org/taxonomy.html>
- Reid, K. F., Callahan, D. M., Carabello, R. J., Phillips, E. M., Frontera, W. R., & Fielding, R. A. (2008). Lower extremity power training in elderly subjects with mobility limitations: A randomized controlled trial. *Aging Clinical and Experimental Research*, 20(4), 337–343.
- Rubenstein, L. Z. (2006). Falls in older people: epidemiology, risk factors and strategies for prevention. *Age and Ageing*, 35 Suppl 2, ii37-ii41. <https://doi.org/10.1093/ageing/afl084>
- Rubenstein, L. Z., & Josephson, K. R. (2002). The epidemiology of falls and syncope. *Clinics in Geriatric Medicine*, 18(2), 141–158.
- Shafer, K. J., Siders, W. A., Johnson, L. K., & Lukaski, H. C. (2009). Validity of segmental multiple-frequency bioelectrical impedance analysis to estimate body composition of adults across a range of body mass indexes. *Nutrition*, 25(1), 25–32. <https://doi.org/10.1016/j.nut.2008.07.004>
- Sherrington, C., Tiedemann, A., Fairhall, N., Close, J. C., & Lord, S. R. (2011). Exercise to prevent falls in older adults: an updated meta-analysis and best practice recommendations. *New South Wales Public Health Bulletin*, 22(3-4), 78–83. <https://doi.org/10.1071/nb10056>
- Shumway-Cook, A., Gruber, W., Baldwin, M., & Liao, S. (1997). The effect of multidimensional exercises on balance, mobility, and fall risk in community-dwelling older adults. *Physical therapy*, 77(1), 46–57.
- Shumway-Cook, A., & Woollacott, M. H. (2007). *Motor control: translating research into clinical practice* (3<sup>rd</sup> ed.). Philadelphia: Lippincott Williams & Wilkins.

- Skevington, S. M., Sartorius, N., & Amir, M. (2004). Developing methods for assessing quality of life in different cultural settings. The history of the WHOQOL instruments. *Social psychiatry and psychiatric epidemiology*, *39*(1), 1–8. <https://doi.org/10.1007/s00127-004-0700-5>
- Starischka, S., Dörning, H., Hagedorn, M., Sieber, L., Schmidt, R. (1991). Zur Diagnostik koordinativ-informationeller Fähigkeiten älterer Menschen – Verfahren und Orientierungswerte. In S. Starischka (Ed.), *Anwendungaspekte sportwissenschaftlicher Forschung* (pp.156-170). Erlensee: SFT-Verlag.
- Steffen, T., & Seney, M. (2008). Test-retest reliability and minimal detectable change on balance and ambulation tests, the 36-item short-form health survey, and the unified Parkinson disease rating scale in people with parkinsonism. *Physical therapy*, *88*(6), 733–746. <https://doi.org/10.2522/ptj.20070214>
- Sturnieks, D. L., Menant, J., Vanrenterghem, J., Delbaere, K., Fitzpatrick, R. C., & Lord, S. R. (2012). Sensorimotor and neuropsychological correlates of force perturbations that induce stepping in older adults. *Gait & Posture*, *36*(3), 356–360. <https://doi.org/10.1016/j.gaitpost.2012.03.007>
- Sturnieks, D. L., St George, R., & Lord, S. R. (2008). Balance disorders in the elderly. *Neurophysiologie clinique = Clinical neurophysiology*, *38*(6), 467–478. <https://doi.org/10.1016/j.neucli.2008.09.001>
- Taylor, M. E., Delbaere, K., Mikolaizak, A. S., Lord, S. R., & Close, J. C. T. (2013). Gait parameter risk factors for falls under simple and dual task conditions in cognitively impaired older people. *Gait & Posture*, *37*(1), 126–130. <https://doi.org/10.1016/j.gaitpost.2012.06.024>
- Thalmann, B., Spiegel, R., Staehelin, H., Brubacher, D., Ermini-Fünfschilling, D., Blaesi, S., & Monsch, A.U. (2002). Dementia screening in general practice: optimised scoring for the Clock Drawing Test. *Brain aging*, *2*(2):36-43.
- Tiedemann, A., Shimada, H., Sherrington, C., Murray, S., & Lord, S. (2008). The comparative ability of eight functional mobility tests for predicting falls in community-dwelling older people. *Age and Ageing*, *37*(4), 430–435. <https://doi.org/10.1093/ageing/afn100>
- Tiedemann, A., Sherrington, C., Close, J. C. T., & Lord, S. R. (2011). Exercise and Sports Science Australia position statement on exercise and falls prevention in older people. *Journal of Science and Medicine in Sport*, *14*(6), 489–495. <https://doi.org/10.1016/j.jsams.2011.04.001>
- Weksler, M. E., & Weksler, B. B. (2012). The epidemic of distraction. *Gerontology*, *58*(5), 385–390. <https://doi.org/10.1159/000338331>
- Whitney, S. L., Wrisley, D. M., Marchetti, G. F., Gee, M. A., Redfern, M. S., & Furman, J. M. (2005). Clinical measurement of sit-to-stand performance in people with balance disorders: Validity of data for the Five-Times-Sit-to-Stand Test. *Physical therapy*, *85*(10), 1034–1045.
- Woollacott, M. H., & Shumway-Cook, A. (1990). Changes in posture control across the life span—a systems approach. *Physical therapy*, *70*(12), 799–807.
- World Health Organization (2007). *WHO global report on falls prevention in older age*. Geneva: World Health Organization (WHO).
- Yardley, L., Beyer, N., Hauer, K., Kempen, G., Piot-Ziegler, C., & Todd, C. (2005). Development and initial validation of the Falls Efficacy Scale-International (FES-I). *Age and Ageing*, *34*(6), 614–619. <https://doi.org/10.1093/ageing/afi196>

## Publication III

### **EFFECTS OF A SUPERVISED VERSUS AN UNSUPERVISED COMBINED BALANCE AND RESISTANCE TRAINING PROGRAM ON BALANCE AND MUSCLE POWER IN HEALTHY OLDER ADULTS: A RANDOMIZED CONTROLLED TRIAL**

André Lacroix<sup>1</sup>, Reto W. Kressig<sup>2</sup>, Thomas Muehlbauer<sup>1</sup>, Yves J. Gschwind<sup>2</sup>, B. Pfenninger<sup>3</sup>, Othmar Bruegger<sup>3</sup> & Urs Granacher<sup>1</sup>

<sup>1</sup> Division of Training and Movement Science, University of Potsdam, Potsdam, Germany

<sup>2</sup> University Center for Medicine of Aging Basel, Felix Platter-Hospital Basel, Basel, Switzerland

<sup>3</sup> Swiss Council for Accident Prevention, Bern, Switzerland

## Reference

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## Abstract

### *Background*

Losses in lower extremity muscle strength/power, muscle mass and deficits in static and particularly dynamic balance due to aging are associated with impaired functional performance and an increased fall risk. It has been shown that the combination of balance and resistance training (CRT) mitigates these age-related deficits. However, it is unresolved whether supervised versus unsupervised CRT is equally effective in improving muscle power and balance in older adults.

### *Objective*

This study examined the impact of a 12-week CRT program followed by 12 weeks of detraining on measures of balance and muscle power in healthy older adults enrolled in supervised (SUP) or unsupervised (UNSUP) training.

### *Methods*

Sixty-six older adults (men: 25, women: 41; age  $73 \pm 4$  years) were randomly assigned to a SUP group (2/week supervised training, 1/week unsupervised training;  $n = 22$ ), an UNSUP group (3/week unsupervised training;  $n = 22$ ) or a passive control group (CG;  $n = 22$ ). Static (i.e., Romberg Test) and dynamic (i.e., 10-m walk test) steady-state, proactive (i.e., Timed Up and Go Test, Functional Reach Test), and reactive balance (e.g., Push and Release Test), as well as lower extremity muscle power (i.e., Chair Stand Test; Stair Ascent and Descent Test) were tested before and after the active training phase as well as after detraining.

### *Results*

Adherence rates to training were 92 % for SUP and 97 % for UNSUP. CRT resulted in significant Group  $\times$  Time interactions. Post-hoc analyses showed, among others, significant training-related improvements for the Romberg Test, stride velocity, Timed Up and Go Test, and Chair Stand Test in favor of the SUP group. Following detraining, significantly enhanced performances (compared to baseline) were still present in 13 variables for the SUP group and in ten variables for the UNSUP group.

*Conclusion*

Twelve weeks of CRT proved to be safe (no training-related injuries) and feasible (high attendance rates of > 90 %). Deficits of balance and lower extremity muscle power can be mitigated by CRT in healthy older adults. Additionally, supervised as compared to unsupervised CRT was more effective. Thus, it is recommended to counteract intrinsic fall risk factors by applying supervised CRT programs for older adults.

**Keywords:** sensorimotor training; resistance training; gym-based/home-based training; de-training; seniors

## Introduction

With increasing age, physical inactivity together with degenerative processes in the central nervous (e.g., loss of sensory and motor neurons) and muscular system (e.g., loss of type-II muscle fibers) result in impaired balance and muscle strength/power performance (Granacher, Zahner, & Gollhofer, 2008). These declines have a major impact on the occurrence of falls. Falls are caused by intrinsic (e.g., muscle weakness, visual disorder, cognitive impairment) and extrinsic (e.g., medication, lighting conditions, stairs) factors, or a combination of both (Schott & Kurz, 2008). Deficits in balance, gait instability, and muscle weakness represent the most important intrinsic fall risk factors in older adults (Rubenstein, 2006). Recently, Rapp et al. (2014) observed that in Germany, 29.7 % of community-dwelling men and 38.7 % of women aged 65 to 90 years fall at least once per year. Rate of falls rises from old to oldest old people, with institutionalized persons being at highest risk for falls and consequential complications (1.7 falls per year; community-living older persons: 0.7 falls per year) (Rubenstein, 2006). Falls cause serious injuries, contribute to immobility in terms of a decline in the ability to perform activities of daily living, and are responsible for premature nursing home admission (Tinetti, 2003). Consequently, there is a need for a widespread implementation of cost-efficient and easy to administer fall-prevention programs for people at risk.

Fall-preventive intervention programs should particularly include exercises that have the potential to mitigate intrinsic fall risk factors like muscle weakness, balance deficits, and gait instability (Rubenstein, 2006). In the past, a large number of studies investigated the effects of resistance and balance training in older adults (e.g., Gillespie et al., 2012; Granacher et al., 2008; Liu & Latham, 2009). Liu and Latham (2009) illustrated in a meta-analysis that progressive resistance training resulted in enhancements of muscle strength and physical ability (e.g., physical domain of the SF-36-questionnaire) in older adults. Additionally, it has been reported that balance training has the potential to improve balance performance, muscle strength, and fall rate in older adults (Granacher et al., 2008). More specifically, Gillespie et al. (2012) showed in a meta-analysis that combined balance and resistance training has the potential to reduce the fall rate in older adults, whereas resistance training alone had no significant effect.

In the past, fall-preventive exercise programs have been implemented as supervised (SUP) or unsupervised home-based (UNSUP) programs (Liu & Latham, 2009). If the goal is to cost-effectively implement fall-preventive exercise programs for large populations, it has to be taken into consideration that a great amount of older people may not have the ability or moti-

vation to participate in a gym-based program (Cohen-Mansfield, Marx, & Guralnik, 2003). In fact, findings from a recent study (Franco et al., 2015) indicate that older adults with a history of falls prefer to participate in exercise programs that can be conducted at home or require no transport. However, the benefits of implementing cost-effective exercise programs (UNSUP) have to be evaluated with regards to their potential on mitigating intrinsic fall risk factors. Earlier studies that investigated the effects of UNSUP vs. SUP after a combined balance and resistance training (CRT) in the older population provided only preliminary evidence (Cyarto, Brown, Marshall, & Trost, 2008; Donat & Oezcan, 2007; Helbostad, Sletvold, & Moe-Nilssen, 2004; Tuunainen et al., 2013; Wu, Keyes, Callas, Ren, & Bookchin, 2010). Some of these studies indicate a slight superiority of SUP regarding improvements in balance and leg strength (Cyarto et al., 2008; Donat & Oezcan, 2007; Tuunainen et al., 2013; Wu et al., 2010), while others do not (Helbostad et al., 2004). Results of studies indicating a superiority of SUP are not consistent, as they detected either a superiority regarding effects on static balance in SUP vs. UNSUP (Cyarto et al., 2008; Wu et al., 2010) or an additional improvement of leg strength in SUP (Donat & Oezcan, 2007). Further, previous studies are limited in as much as they tested specific components of balance only (e.g., static but not dynamic, proactive and reactive balance) (Tuunainen et al., 2013), or conducted different and thus not comparable training protocols (e.g., varying volumes) in the intervention groups (IGs) (Helbostad et al., 2004; Tuunainen et al., 2013). Other studies did not follow a randomized controlled trial (RCT) approach (e.g., Donat & Oezcan, 2007), or implemented only a quasi-unsupervised intervention group in which participants received additional supervised exercise sessions (Cyarto et al., 2008). Due to the heterogeneous and controversial results with tendencies indicating a superiority of SUP, there is a need for studies providing a clearer and more comprehensive view on the effects of supervision in older adults. To the authors' knowledge, no study compared the effects of a supervised versus an unsupervised CRT and an inactive control group (CG) on static/dynamic steady-state, proactive, and reactive balance as well as lower extremity muscle power in healthy older adults.

Further, information on detraining effects is important to document robustness of possible training-related adaptations. Especially older people may be prone to longer periods of training cessation because of their high susceptibility to diseases, injuries, or personal factors like family commitments or even extended travels. However, there are only a few studies available which examined detraining effects following CRT and reported contradictory findings (e.g., Carvalho, Marques, & Mota, 2009; Helbostad et al., 2004; Seco et al., 2013).



Thus, the aims of this study were (1) to examine the effects of a 12-week CRT on measures of static/dynamic steady-state, proactive, and reactive balance, lower extremity muscle power (primary outcomes), falls efficacy, cognitive function, quality of life, and body composition (secondary outcomes) in healthy older adults; (2) to compare the effects of SUP versus UNSUP; and (3) to detect detraining effects. The authors hypothesized that (1) CRT results in significant improvements in primary and secondary outcomes as compared to the CG; (2) the SUP group shows larger performance enhancements as compared to the UNSUP group, and (3) training-related improvements will remain above baseline values after 12 weeks of detraining in both training groups.

## **Methods**

To test the hypotheses, an RCT design was used. Measurements were conducted before and after training and 12 weeks after training completion.

### *Participants*

Sixty-six community-dwelling healthy adults (men: 25, women: 41) aged 65-80 years participated in this RCT [ClinicalTrials.gov ID: NCT01906034; (Gschwind et al., 2013)]. Trial participants were recruited by posting flyers and by publishing articles in local newspapers. After the experimental procedure was explained, participants gave their written informed consent. All participants were able to walk independently and did not use any walking aids. Eligibility was examined with a standard protocol, which comprised the assessment of demographic and anthropometric data, relevant diseases, recent operations, acute injuries, and drug intake to detect contraindications to training. We deemed participants as generally healthy if no relevant diseases (e.g., neurophysiologic, cardiovascular, vestibular/gait disorder) were reported. Participants were excluded, if they did not reach cut-off scores for the Mini Mental State Examination (MMSE; < 24 points) (Folstein, Folstein, & McHugh, 1975) and the Clock Drawing Test (CDT; pathological test performance) (Thalman et al., 2002). Additionally, subjects were excluded if they participated in a regular balance and/or resistance training program six months prior to the start of the study. All inclusion and exclusion criteria were specified prior to the beginning of the study.

**Table 1:** Baseline characteristics by group.

Measure	SUP ( <i>n</i> = 22)	UNSUP ( <i>n</i> = 22)	CG ( <i>n</i> = 22)
Males/females	8/14	8/14	9/13
Age (years)	72.7 (4.0)	73.1 (3.6)	72.7 (3.8)
Body height (cm)	166.2 (7.7)	168.9 (12.2)	168.6 (9.0)
Body mass (kg)	69.9 (10.7)	73.7 (12.1)	74.1 (15.8)
Body mass index (kg/m <sup>2</sup> )	25.2 (3.1)	26.0 (5.0)	25.9 (3.9)
Total body water (l)	35.6 (6.5)	36.8 (8.5)	37.5 (8.6)
Total skeletal muscle mass (kg)	26.5 (5.3)	27.3 (6.8)	27.9 (6.8)
MMSE (score)	27.8 (1.7)	28.4 (1.6)	28.5 (1.3)
CDT (performance)	all participants were classified as non-pathological		
Physical activity (h/week)	15.4 (11.4)	17.9 (13.2)	14.3 (10.7)
Handgrip strength (kg)	29.7 (7.7)	27.0 (8.8)	28.5 (8.7)

Values are means with standard deviations in parentheses. *CDT* = Clock Drawing Test; *CG* = control group; *MMSE* = Mini Mental State Examination; *SUP* = 2 x supervised, 1 x unsupervised training/week; *UNSUP* = 3 x unsupervised training/week. No group baseline differences were detected (all  $p > 0.05$ ).

Participants were randomly assigned to two intervention groups (*SUP*, *UNSUP*) or a *CG* (i.e., no training). The randomization process was conducted with Research Randomizer ([www.randomizer.org](http://www.randomizer.org)). Figure 1 shows a flow chart of the study design. Participants' baseline characteristics are presented in Table 1. The study was approved by the ethics committee of the University of Potsdam (reference number: 34/2012) and conducted according to the ethical standards of the latest version of the Declaration of Helsinki.

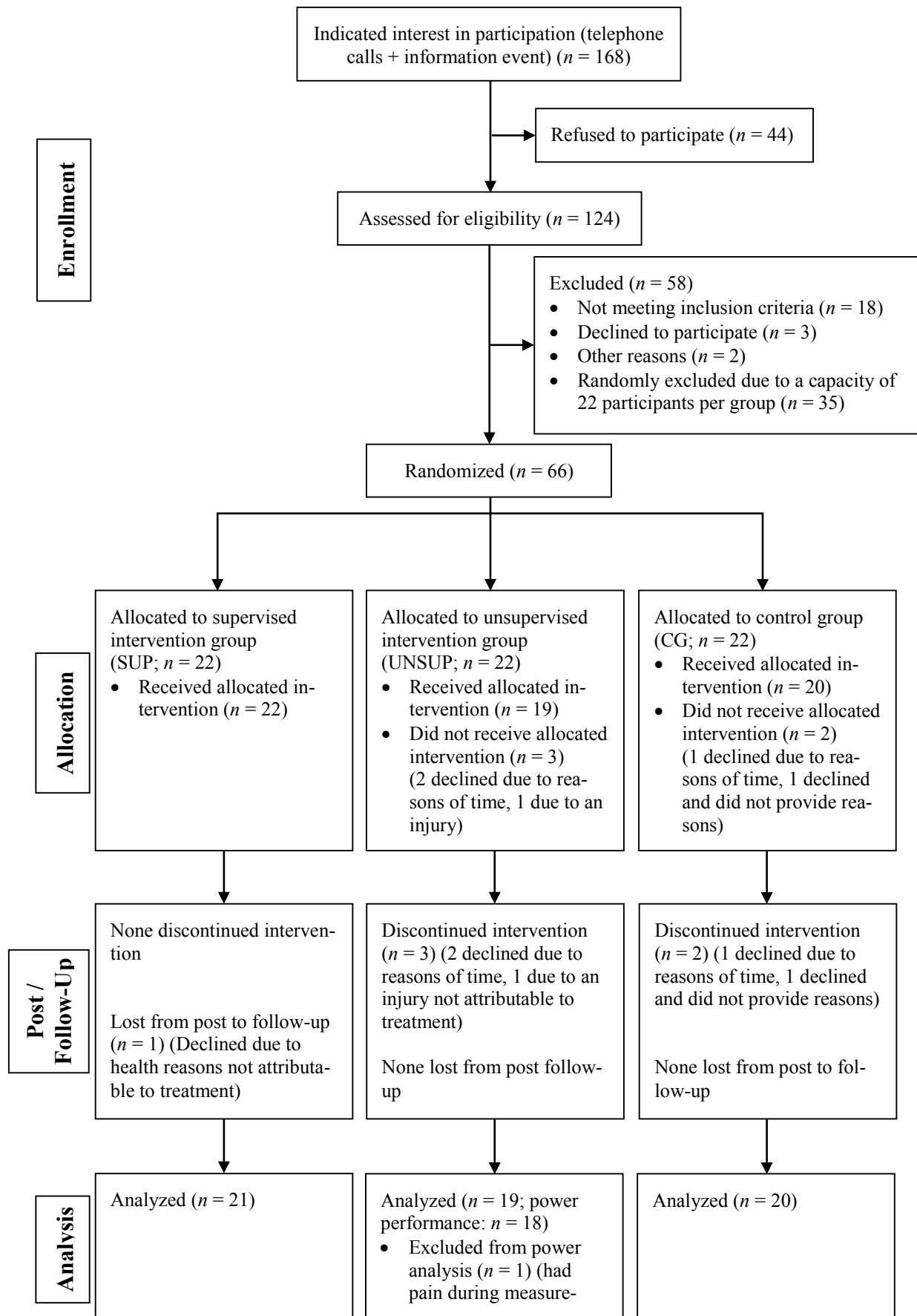


Figure 1: Flowchart of the study design.

### *Combined balance and resistance training (CRT)*

Participants of the two IGs conducted a 12-week CRT program with three training sessions per week. The exercise program was based on recommendations developed by an expert panel which is publicly accessible (<http://www.stuerze.bfu.ch>). Progressive exercise routines with different intensity stages were compiled from the given exercises. In general, exercises were performed using participants' own body weight or with the help of small, low-cost equipment (e.g., towels, bottles, balls). The intensity of the training was examined with the help of a perceived exertion rating scale (Borg scale; 6-20 points) (Borg, 1982). Participants were asked to perform each exercise with a rate of perceived exertion of 12-16 ('somewhat hard' to 'hard'). A single training session comprised either static balance exercises, dynamic balance exercises or strength/power exercises for leg and trunk muscles. Before the beginning of the intervention, all subjects were extensively introduced to the exercise program, training principles, and potential risks. Table 2 illustrates the training protocol. For a detailed description see Granacher, Muehlbauer, Gschwind, Pfenninger, and Kressig (2014).

The SUP group exercised twice a week at a local gym, supervised by an instructor and once a week unsupervised at home. For the home-based sessions, an illustrated exercise book was provided to all participants (Granacher et al., 2011). Participants also received a training log and were asked to document each completed training session and the respective stage of progression. The UNSUP group followed the same exercise routine as SUP group, except that they trained unsupervised at home only (three times per week). Quality and quantity of the training were controlled by phone calls every fortnight. Participants of the CG maintained their habitual physical activity level. They did not take up new sports-related activities during the experimental period and received a supervised 12-week program after the trial.

### *Testing procedure*

All tests were conducted at our biomechanics laboratory by the same assessor (graduated sport scientist). Participants received standardized verbal instructions regarding the test procedure. Subsequently, subjects were asked to answer the following questionnaires [i.e., pre-test: MMSE, CDT, Freiburg questionnaire of physical activity (FQoPA)]. Thereafter, the testing started. Pre-, post-, and follow-up (12 weeks after the intervention) tests included (1) questionnaires [i.e., falls efficacy scale-international (FES-I), digit symbol substitution test (DSST), World Health Organization quality of life-bref (QoL)], measurement of anthropometric data (e.g., body height, body mass), and body composition (e.g., lean tissue mass of the

legs, skeletal muscle mass); (2) a five-minute warm-up program on a bicycle ergometer at a rate of perceived exertion of 12 ('somewhat hard') on the Borg scale; (3) measurement of static/dynamic steady-state, proactive, and reactive balance; and (4) the analysis of lower extremity muscle power. Additionally, handgrip strength was assessed at baseline. Prior to testing, participants performed one to three practice trials for each test. Balance tests were performed before the power tests to prevent muscle fatigue. If several trials were conducted for one test, mean values were used for further data analysis.

**Table 2:** Protocol of the training program.

<b>Training protocol</b>	
<i>Exercises</i>	(1) Static balance exercises (basic exercise: upright, bipedal stance) (2) Dynamic balance exercises (basic exercise: normal gait) (3) Strength/power exercises for the lower extremities and trunk muscles (basic exercises: squats, plank, standing side leg lifts, calf raises / toe raises, standing trunk extensions)
<i>Training volume</i>	<ul style="list-style-type: none"> <li>– 12-week training program with a total of 36 sessions</li> <li>– Each session lasted 45 min (inclusive 15 min warm-up and cool-down)</li> <li>– Static balance exercises               <ul style="list-style-type: none"> <li>– 4 series, each lasting 20 s</li> <li>– 30 s rest between series</li> </ul> </li> <li>– Dynamic balance exercise sessions               <ul style="list-style-type: none"> <li>– 4 series, each lasting 20-60 s</li> <li>– 30 s rest in between the series</li> </ul> </li> <li>– Strength/power exercise sessions               <ul style="list-style-type: none"> <li>– 3 series, each consisted of 8-15 repetitions</li> <li>– 60-120 s rest between series</li> <li>– Muscle groups: thigh, abdominal, gluteal, calf / shin, and upper / lower back</li> </ul> </li> </ul>
<i>Training frequency</i>	– 3 training sessions per week (on non-consecutive days)
<i>Training intensity</i>	<ul style="list-style-type: none"> <li>– Progressive exercise routines for static/dynamic balance exercises               <ul style="list-style-type: none"> <li>– reduction of base of support (bipedal – semi-tandem – tandem – one-legged stance; normal – narrow – overlapping – tandem gait)</li> <li>– reduction of visual input</li> <li>– weight shifts</li> <li>– changes of gait rhythm / direction / velocity</li> <li>– additional motor / cognitive tasks</li> <li>– inclusion of unstable surfaces (e.g., foam cushions, towels)</li> <li>– combinations of these variations</li> </ul> </li> <li>– Progressive exercise routines for strength/power exercises               <ul style="list-style-type: none"> <li>– from slow to fast movement velocity</li> <li>– increasing lever arms and involvement of multiple joints</li> <li>– from static to dynamic exercises</li> <li>– additional movements of arms and legs</li> <li>– inclusion of unstable surfaces (e.g., foam cushions, towels)</li> </ul> </li> </ul>

## *Testing material*

### *Assessment of balance*

Static steady-state balance was assessed using the modified Romberg Test (ROM) (Agrawal, Carey, Hoffman, Sklare, & Schubert, 2011) while standing on a three-dimensional force plate (Leonardo 105 Mechanograph<sup>®</sup>, Novotec Medical GmbH, Pforzheim, Germany). Participants stood in an upright position on a balance pad (Airex<sup>®</sup>) for 30 s without shoes, feet shoulder width apart, and arms fully extended in front of the body with palms facing upwards, and eyes closed. The test was terminated if participants opened their eyes, moved their arms or feet in order to achieve stability or required operator intervention. Standing time (s) and the path velocity (mm/s) of the center of force (CoF) were assessed. If a subject failed, an additional trial was provided. For the modified ROM, a high test-retest and interrater reliability has been shown previously (Granacher et al., 2014).

Dynamic steady-state balance was tested while walking on a 10-meter walkway using the OptoGait<sup>®</sup> system (Microgate, Bolzano, Italy). The OptoGait<sup>®</sup> system is an opto-electric system with bars of one meter length. Each bar contains 100 LEDs, which continuously transmit to receiving bars. Spatio-temporal gait data were registered at 1,000 Hz. Participants were asked to walk at their habitual walking speed wearing their own footwear. Each walk was initiated and terminated a minimum of two meters before and after the walkway to allow sufficient distance to accelerate and decelerate. Stride velocity (distance in meter covered per second during one stride) and stride length (distance in cm between successive heel contacts of the same foot) as well as the corresponding coefficients of variation (CV; standard deviation (SD)/mean  $\times$  100) were analyzed. The higher the CV value, the more unstable the walking pattern. Since motor-cognitive integration is impaired in old age, dynamic steady-state balance was tested under single and dual task conditions. For the dual task condition, participants had to recite out loud subtractions by three starting from a randomly selected number between 300 and 900. One test trial was performed for each condition. The OptoGait<sup>®</sup> system demonstrated high test-retest reliability (Lee et al., 2014) as well as high discriminant and concurrent validity (Lienhard, Schneider, & Maffioletti, 2013).

Proactive balance was measured using the Functional Reach Test (FRT) (Duncan, Weiner, Chandler, & Studenski, 1990) and the Timed Up and Go Test (TUG) (Podsiadlo & Richardson, 1991). The FRT measures the ability to reach forward while maintaining a fixed base of support in the standing position. Participants stood with their feet shoulder width apart on a

force plate (Leonardo 105 Mechanograph<sup>®</sup>). They were asked to lift their dominant arm and make a fist. Following an acoustic signal, they reached forward as far as they could along a height-adjustable tape measure. Three tests of twelve seconds were performed. A trial was terminated, if subjects took a step or touched the tape measure. Maximal reach distance (cm) and the path velocity (mm/s) of the CoF were assessed. The FRT proved to be reliable (Duncan et al., 1990) and valid (Newton, 2001). For the TUG, participants were asked to sit down in a chair (height: 46 cm) and place their arms on the armrests. After the command “ready-set-go”, they had to stand up, walk three meters at their habitual walking speed, turn around and sit down again. Two test trials were performed. Time was recorded with a stopwatch to the nearest 0.01 s. The TUG showed excellent test-retest reliability in older adults (Podsiadlo & Richardson, 1991).

To test reactive balance, a mediolateral (ML) perturbation impulse was applied while participants stood on a two-dimensional balance platform (Posturomed; Haider Bioswing, Pullenreuth, Germany). The platform was free to move in the transversal plane. The mechanical constraints and the reliability of the system were described earlier (Mueller, Gunther, Krauss, & Horstmann, 2004). During the experiment, the platform was moved 2.5 cm from the neutral position and magnetically fixed. Participants were asked to stand on the platform in a narrow step stance, hands placed on their hips and gaze fixated on a cross at the nearby wall. The perturbation impulse was unexpectedly applied by detaching the magnet. Participants’ task was to stand as still as possible over a period of 10 s. A trial was skipped, if the subject changed the position of the feet or took the hands off the hips. Three test trials were performed. Summed oscillations of the platform in ML and anterior-posterior (AP) directions were assessed in centimeters.

Reactive balance was additionally tested using the clinical Push and Release Test (PRT) (Jacobs, Horak, van Tran, & Nutt, 2006). The PRT rates the postural response to a sudden release. Subjects were asked to stand barefooted in comfortable stance. They had to push backward against the palms of the examiner’s hands placed on the subject’s scapulae. When the shoulders and hips moved to a stable position just behind the heels, the examiner suddenly removed the hands, requiring the participant to take at least one backward step to regain balance. The amount of steps and the quality of the recovery was rated according to the following scale: 0 = 1 step, 1 = 2-3 small steps with independent recovery, 2 =  $\geq$  4 steps with independent recovery, 3 = steps with assistance for recovery, 4 = fall or unable to stand without

assistance. Three test trials were conducted. The PRT proved to be reliable and valid (Jacobs et al., 2006).

#### *Assessment of lower extremity muscle power*

Lower extremity muscle power was assessed using the Chair Stand Test (CST) while standing on a force plate (Leonardo 105 Mechanograph<sup>®</sup>) (Csuka & McCarty, 1985). In addition, the Stair Ascent and Descent Test (SADT) was applied (Tiedemann, Shimada, Sherrington, Murray, & Lord, 2008). To perform the CST, subjects had to sit on a chair with arms folded across the chest. After an acoustic signal, participants had to stand up and sit down five times as quickly as they could. A trial was cancelled if an upright stance was not achieved, the subject did not touch the chair after the downward movement, the feet left the initial position or the arms were used to stand up. Performance was measured with the force plate and the associated software to the nearest 0.01 s as the time from the initial to the final seated position. Additionally, the average (five rises) maximum power per kilogram body weight ( $P_{\max}$ ; W/kg) was recorded. Three test trials were conducted. Excellent test-retest reliability was reported (Tiedemann et al., 2008).

For the SADT, participants were instructed to ascend an eight-stair flight at a fast but safe velocity (stair height: 17.1 cm). Time for ascending and descending the stairs was registered separately to the nearest 0.01 s. Timing for the Stair Ascent Test (SAT) began after the subject lifted the foot off the ground and stopped when both feet were placed on the eighth step. Accordingly, timing for the Stair Descent Test (SDT) stopped when both feet reached ground level. Additionally, stair climb power was calculated using the formula:  $power = force \times velocity$  and reported in W/kg (Bean, Kiely, LaRose, Alian, & Frontera, 2007). One test trial was conducted. Test-retest reliability was reported and proved to be good (Tiedemann et al., 2008).

At baseline, handgrip strength of the dominant hand was measured using a Jamar hand dynamometer (Sammons Preston Inc., Bolingbrook, USA). Participants had to sit with both arms parallel to the body. After the instruction “ready-set-go”, subjects had to continuously increase their grip until maximal force was reached.

#### *Assessment of body composition*

A non-invasive bioelectrical impedance analysis (BIA) was conducted using an eight-electrode impedance meter (InBody 720; BioSpace, Seoul, Korea). Alternating currents of



100 and 500  $\mu\text{A}$  at frequencies of 1, 5, 50, 250, 500, and 1,000 kHz were applied to measure impedance of arms, trunk, and legs. Body mass (kg), body mass index (BMI;  $\text{kg}/\text{m}^2$ ), total body water (l), lean tissue mass of the legs (sum of left plus right leg; kg), and total skeletal muscle mass (kg) were assessed. Subjects stood barefoot on the device with arms abducted to approximately  $40^\circ$ . They held electrodes in both hands while the feet were placed on the appropriate electrodes. Participants were instructed to abstain from caffeine and alcohol for 24 hours, and exercise for 12 hours prior to testing. The InBody 720 proved to be a valid estimator of lean body mass in men and women ( $r^2 = 0.52\text{-}0.95$ ) (Anderson, Erceg, & Schroeder, 2012).

#### *Statistical analyses and sample size*

Data are presented as group mean values  $\pm$  SD or medians (Md) and interquartile ranges (IQR). An a priori power analysis using G\*Power (Faul, Erdfelder, Lang, & Buchner, 2007) with the following input parameters was conducted to obtain medium-sized Group  $\times$  Time interaction effects: effect size (i.e.,  $f = 0.25$ ), type I error (i.e., 0.05), type II error (i.e., 0.90), number of groups (i.e., 3), number of measurements (i.e., 3), and correlation among groups (i.e., 0.40). In addition, a dropout rate of 20 % was considered. The use of a medium effect size was based on a similar study conducted by Granacher et al. (2011) who investigated the effects of CRT on measures of balance (e.g., gait velocity) and lower extremity muscle strength in middle-aged adults. Our analysis revealed a total sample size of 65-66 (i.e., 22 participants per group). To analyze baseline differences, a multivariate analysis of variance (ANOVA) was computed. Measures of balance and muscle power as well as questionnaires and body composition parameters were analyzed in separate 3 (Group: SUP, UNSUP, CG)  $\times$  3 (Time: pre, post, follow-up) ANOVAs with repeated measures on Time. If baseline differences were computed, pretest values were used as covariates. Bonferroni-adjusted post-hoc tests ( $t$  Tests, Wilcoxon Tests) were performed to detect statistically significant time differences in the groups. Kruskal-Wallis one-way ANOVA and Friedman Tests were used for nonparametrical variables and to control results of parametrical tests, if normal distribution (Kolmogorov-Smirnov Test) and homogeneity of variances (Levene's Test) could not be assumed. If differences occurred, nonparametrical data were outlined. Effect sizes (Cohen's  $d$ ) were determined which are indicative of the effectiveness of a treatment and help to assess whether a statistically significant difference is of practical concern. Cohen's  $d$  values  $\leq 0.49$  indicate small,  $0.50 \leq d \leq 0.79$  medium, and  $\geq 0.80$  large effects (Cohen, 1988). Changes

within groups were calculated by the formula  $d = \text{mean}_{\text{pre}} - \text{mean}_{\text{post}} / \text{SD}_{\text{pre}}$  (Leonhart, 2004) to allow comparison with former studies. Depending on the outcome parameter,  $d$  can turn out to be positive or negative. To improve readability, any performance improvement within a group was reported with a positive  $d$  and performance deteriorations with a negative  $d$ . Additionally,  $PS_{\text{dep}}$  scores (probability of superiority for dependent samples) were computed as an estimate of effect sizes in nonparametrical post-hoc tests (Grissom & Kim, 2012). Analyses were performed with the Statistical Package for Social Sciences version 22. The significance level was set at  $p < 0.05$ .

## Results

The baseline characteristics (Table 1) indicate that the older adults of this study were physically active with an activity level of more than 14 hours per week in each group. ANOVA revealed no significant baseline differences for age, anthropometric data, body composition, cognitive performance, physical activity, and handgrip strength between groups (all  $p > 0.05$ ). None of the participants reported any training or test-related injuries. Both intervention groups showed high attendance rates during the training period [SUP: 91.7 % (unsupervised sessions: 94.7 %); UNSUP: 97.4 %]. Means and SDs for all primary outcome variables are shown in Tables 3 and 4. Tables 5 and 6 display the repeated measure ANOVA results.

### *Static steady-state balance*

The statistical analysis for the ROM revealed a significant Group  $\times$  Time interaction effect for standing time ( $d = 1.04$ ), but not for path velocity ( $d = 0.36$ ). Post-hoc analyses revealed significant increases in standing time from pre to post for SUP ( $d = 1.00$ ) and from pre to follow-up ( $d = 0.80$ ), but no significant changes in UNSUP (pre–post:  $d = 0.33$ ; pre–follow-up:  $d = 0.09$ ) and CG (pre–post:  $d = -0.37$ ; pre–follow-up:  $d = -0.01$ ). No significant changes were found from post to follow-up testing.

### *Dynamic steady-state balance (single task walking)*

For the parameters stride velocity and stride length, significant Group  $\times$  Time interactions were found (stride velocity:  $d = 0.74$ ; stride length:  $d = 0.60$ ). Post-hoc tests showed significant improvements from pre to post in stride velocity for SUP ( $d = 0.62$ ), but not in stride length ( $d = 0.26$ ). From pre to follow-up, significant increases were found for SUP in both parameters (stride velocity:  $d = 0.69$ ; stride length:  $d = 0.33$ ). No significant changes were

detected for UNSUP from pre to post (stride velocity:  $d = 0.24$ ; stride length:  $d = 0.06$ ) and from pre to follow-up (stride velocity:  $d = 0.35$ ; stride length:  $d = 0.13$ ). Similarly, no significant changes were found for CG from pre to post (stride velocity:  $d = -0.17$ ; stride length:  $d = -0.13$ ) and from pre to follow-up (stride velocity:  $d = -0.01$ ; stride length:  $d = -0.01$ ). No significant changes occurred from post to follow-up testing.

For stride velocity and stride length CV, Group  $\times$  Time interactions reached the level of significance for both parameters, stride velocity ( $d = 0.86$ ) and stride length ( $d = 0.65$ ). Post-hoc tests revealed a significant decrease in the SUP (i.e., performance enhancement) for both parameters from pre to post (CV stride velocity:  $d = 0.73$ ; CV stride length:  $d = 0.72$ ), but not from pre to follow-up (CV stride velocity:  $d = 0.16$ ; CV stride length:  $d = 0.38$ ). Additionally, SUP significantly decreased performance in stride velocity CV from post to follow-up ( $d = -1.09$ ). No significant performance changes were found for UNSUP from pre to post (CV stride velocity:  $d = -0.74$ ; CV stride length:  $d = -0.33$ ) and from pre to follow-up (CV stride velocity:  $d = -0.28$ ; CV stride length:  $d = -0.24$ ). Likewise, no performance changes were observed for CG from pre to post (CV stride velocity:  $d = -0.18$ ; CV stride length:  $d = -0.19$ ) and from pre to follow-up (CV stride velocity:  $d = 0.05$ ; CV stride length:  $d = -0.03$ ). No significant changes were found for UNSUP and CG from post to follow-up testing.

#### *Dynamic steady-state balance (dual task walking)*

For the parameters stride velocity and stride length, the statistical analysis did not reveal significant Group  $\times$  Time interactions (stride velocity:  $d = 0.43$ ; stride length:  $d = 0.33$ ). Similarly, no significant Group  $\times$  Time interactions were found for CV parameters (stride velocity:  $d = 0.39$ ; stride length:  $d = 0.37$ ).

**Table 3:** Effects of the combined balance and resistance training program on balance performance in healthy older adults.

Measure	SUP ( <i>n</i> = 21)			UNSUP ( <i>n</i> = 19)			CG ( <i>n</i> = 20)					
	pre	post	follow-up	<i>d</i> pre-post / follow-up	pre	post	follow-up	<i>d</i> pre-post / follow-up	pre	post	follow-up	<i>d</i> pre-post / follow-up
<i>Static steady-state balance</i>												
Mod. Romberg Test (s) <sup>a</sup>	12.8 (8.7)	21.5 (8.6)	19.7 (9.3)	1.00 <sup>b</sup> / 0.80 <sup>b</sup>	6.4 (5.7)	8.2 (5.7)	6.9 (6.2)	0.33 / 0.09	16.0 (9.4)	12.5 (9.3)	15.9 (9.3)	-0.37 / -0.01
Mod. Romberg Test (mm/s)	102.7 (30.9)	100.5 (27.5)	91.4 (24.3)	0.07 / 0.37	137.8 (34.6)	137.9 (42.2)	130.1 (38.5)	-0.003 / 0.22	110.9 (34.5)	109.1 (34.1)	101.8 (32.9)	0.05 / 0.26
<i>Dynamic steady-state balance</i>												
Stride velocity (m/s) <sup>a</sup>	1.38 (0.13)	1.46 (0.12)	1.47 (0.13)	0.62 <sup>b</sup> / 0.69 <sup>b</sup>	1.37 (0.17)	1.41 (0.16)	1.43 (0.14)	0.24 / 0.35	1.37 (0.18)	1.34 (0.17)	1.37 (0.13)	-0.17 / -0.01
Stride length (cm) <sup>a</sup>	141.4 (14.9)	145.3 (12.4)	146.3 (13.5)	0.26 / 0.33 <sup>b</sup>	142.7 (17.6)	143.7 (19.3)	144.9 (16.6)	0.06 / 0.13	140.6 (15.2)	138.7 (15.0)	140.5 (12.4)	-0.13 / -0.01
CV stride velocity (%) <sup>a</sup>	2.91 (1.32)	1.94 (0.70)	2.70 (1.10)	0.73 <sup>b</sup> / 0.16	2.58 (0.78)	3.16 (1.22)	2.80 (0.85)	-0.74 / -0.28	2.27 (0.79)	2.41 (1.17)	2.23 (0.97)	-0.18 / 0.05
CV stride length (%) <sup>a</sup>	2.26 (0.81)	1.68 (0.79)	1.95 (0.88)	0.72 <sup>b</sup> / 0.38	2.05 (0.82)	2.32 (1.16)	2.25 (0.71)	-0.33 / -0.24	1.74 (0.58)	1.85 (0.95)	1.76 (0.80)	-0.19 / -0.03
Stride velocity dual task (m/s)	1.24 (0.16)	1.31 (0.17)	1.35 (0.17)	0.44 / 0.69 <sup>b</sup>	1.22 (0.22)	1.20 (0.22)	1.26 (0.17)	-0.09 / 0.18	1.17 (0.23)	1.16 (0.18)	1.23 (0.14)	-0.04 / 0.26
Stride length dual task (cm)	135.5 (15.7)	137.7 (13.4)	139.5 (14.6)	0.14 / 0.25	135.4 (21.0)	133.3 (19.6)	136.2 (17.8)	-0.10 / 0.04	130.5 (13.8)	130.3 (16.0)	133.2 (13.5)	-0.01 / 0.20
CV stride velocity dual task (%)	3.83 (1.67)	3.31 (1.50)	3.56 (1.28)	0.31 / 0.16	3.99 (1.44)	4.36 (2.76)	3.91 (1.73)	-0.26 / 0.06	4.18 (2.24)	4.18 (1.89)	3.35 (1.61)	-0.001 / 0.37
CV stride length dual task (%)	2.71 (0.92)	2.37 (0.91)	2.51 (1.10)	0.37 / 0.22	2.90 (0.75)	2.89 (1.5)	2.94 (1.19)	0.01 / -0.05	2.27 (0.70)	2.52 (1.12)	2.14 (0.81)	-0.36 / 0.19

Table 3: continued

Measure	SUP (n = 21)			UNSUP (n = 19)			CG (n = 20)					
	pre	post	follow-up	d post / follow-up	pre	post	follow-up	d post / follow-up	pre	post	follow-up	d post / follow-up
<i>Proactive balance</i>												
TUG (s) <sup>a</sup>	9.91 (1.33)	8.78 (1.08)	8.74 (1.38)	0.85 <sup>b</sup> / 0.88 <sup>b</sup>	9.80 (0.84)	9.43 (1.02)	9.27 (1.01)	0.44 / 0.63 <sup>b</sup>	9.87 (1.35)	9.66 (1.19)	9.62 (0.98)	0.16 / 0.19
FRT (cm) <sup>a</sup>	30.2 (3.2)	36.1 (3.8)	35.5 (3.7)	1.82 <sup>b</sup> / 1.65 <sup>b</sup>	28.3 (4.7)	31.4 (4.8)	32.1 (4.3)	0.65 <sup>b</sup> / 0.79 <sup>b</sup>	32.9 (3.6)	32.2 (3.9)	31.1 (3.8)	-0.18 / -0.48
FRT (mm/s) <sup>a</sup>	34.6 (4.8)	40.0 (7.6)	40.3 (5.5)	1.12 <sup>b</sup> / 1.18 <sup>b</sup>	34.5 (6.0)	37.3 (9.5)	44.0 (13.6)	0.46 / 1.57 <sup>b</sup>	36.1 (7.0)	39.3 (8.5)	39.6 (8.6)	0.46 / 0.50
<i>Reactive balance</i>												
PRT (score) [Md, IQR] <sup>c</sup>	1.33 (0.67)	0.67 (1.0)	1.0 (0.67)	PS <sub>dep</sub> = 0.98 <sup>d</sup> / 0.95 <sup>d</sup>	1.67 (1.0)	1.0 (0.33)	1.0 (0.33)	PS <sub>dep</sub> = 0.95 <sup>d</sup> / 0.84 <sup>d</sup>	1.33 (0.67)	1.0 (0.67)	1.0 (0.33)	PS <sub>dep</sub> = 0.58 / 0.66
Posturomed ML (cm)	14.6 (12.1)	14.2 (9.5)	11.1 (6.0)	0.03 / 0.29	18.7 (13.2)	14.0 (11.7)	12.7 (7.7)	0.36 <sup>b</sup> / 0.45	15.5 (9.2)	9.8 (4.4)	12.6 (6.9)	0.62 <sup>b</sup> / 0.32
Posturomed AP (cm)	4.9 (7.9)	5.4 (7.6)	4.2 (7.0)	-0.06 / 0.09	6.4 (5.2)	5.1 (6.6)	4.8 (4.8)	0.25 / 0.31	4.3 (3.6)	3.2 (2.8)	3.8 (2.9)	0.31 / 0.14

Values are means with standard deviations in parentheses. AP = anterior-posterior; CG = control group; CV = coefficient of variation; d = Cohen's d; FRT = Functional Reach Test; ML = mediolateral; PRT = Push and Release Test; PS<sub>dep</sub> = probability of superiority for dependent samples; SUP = 2 x supervised, 1 x unsupervised training/week; TUG = Timed Up and Go Test; UNSUP = 3 x unsupervised training/week.

<sup>a</sup> Significant Group x Time interaction effect, p < 0.05 (ANOVA with repeated measures on Time)

<sup>b</sup> Significant difference pre vs. post or pre vs. follow-up, p < 0.017 (post-hoc test: dependent t Test)

<sup>c</sup> Significant Group x Time interaction effect, p < 0.001 (Kruskal-Wallis Test)

<sup>d</sup> Significant difference pre vs. post or pre vs. follow-up, p < 0.01 (post-hoc test: Wilcoxon Test)

**Table 4:** Effects of the combined balance and resistance training program on power performance in healthy older adults.

Measure	SUP ( <i>n</i> = 21)				UNSUP ( <i>n</i> = 19)				CG ( <i>n</i> = 20)			
	pre	post	follow-up	<i>d</i> pre-post/follow-up	pre	post	follow-up	<i>d</i> pre-post/follow-up	pre	post	follow-up	<i>d</i> pre-post/follow-up
<i>Lower extremity power</i>												
CST (s) <sup>a</sup>	12.86 (1.86)	9.87 (1.64)	9.98 (1.56)	1.61 <sup>b</sup> / 1.55 <sup>b</sup>	13.39 (1.85)	11.83 (1.78)	11.52 (1.81)	0.84 <sup>b</sup> / 1.01 <sup>b</sup>	11.53 (1.48)	11.67 (1.19)	11.45 (1.12)	-0.09 / 0.05
CST (W/kg) <sup>a</sup>	8.32 (1.55)	10.06 (1.77)	9.86 (1.83)	1.12 <sup>b</sup> / 0.99 <sup>b</sup>	8.45 (1.43)	9.47 (2.06)	9.30 (1.78)	0.71 <sup>b</sup> / 0.59 <sup>b</sup>	9.24 (1.87)	9.23 (1.95)	9.23 (1.80)	-0.01 / -0.01
SAT (s) <sup>a</sup>	5.48 (0.54)	4.57 (0.38)	4.49 (0.38)	1.69 <sup>b</sup> / 1.83 <sup>b</sup>	5.66 (0.82)	4.99 (0.54)	4.93 (0.68)	0.82 <sup>b</sup> / 0.89 <sup>b</sup>	5.07 (0.36)	4.86 (0.33)	4.72 (0.43)	0.58 <sup>b</sup> / 0.97 <sup>b</sup>
SAT (W/kg) <sup>a</sup>	2.53 (0.27)	3.02 (0.25)	3.08 (0.26)	1.81 <sup>b</sup> / 2.04 <sup>b</sup>	2.46 (0.32)	2.77 (0.28)	2.83 (0.35)	0.97 <sup>b</sup> / 1.16 <sup>b</sup>	2.71 (0.20)	2.83 (0.22)	2.92 (0.26)	0.60 <sup>b</sup> / 1.05 <sup>b</sup>
SDT (s) <sup>a</sup>	5.10 (0.66)	3.94 (0.42)	3.94 (0.42)	1.76 <sup>b</sup> / 1.76 <sup>b</sup>	5.16 (0.48)	4.32 (0.50)	4.16 (0.35)	1.75 <sup>b</sup> / 2.08 <sup>b</sup>	4.59 (0.48)	4.39 (0.47)	4.32 (0.46)	0.42 / 0.56 <sup>b</sup>
SDT (W/kg) <sup>a</sup>	2.72 (0.28)	3.52 (0.39)	3.51 (0.36)	2.86 <sup>b</sup> / 2.82 <sup>b</sup>	2.68 (0.23)	3.21 (0.37)	3.31 (0.30)	2.30 <sup>b</sup> / 2.74 <sup>b</sup>	3.02 (0.33)	3.16 (0.38)	3.21 (0.38)	0.42 / 0.58 <sup>b</sup>

Values are means with standard deviations in parentheses. CG = control group; CST = Chair-Stand-Test; *d* = Cohen's *d*; SAT = Stair-Ascent-Test; SDT = Stair-Descent-Test; SUP = 2 x supervised, 1 x unsupervised training/week; UNSUP = 3 x unsupervised training/week.

<sup>a</sup> Significant Group x Time interaction effect, *p* < 0.001 (ANOVA with repeated measures on Time)

<sup>b</sup> Significant difference pre vs. post or pre vs. follow-up, *p* < 0.017 (post-hoc test: dependent *t* Test)

**Table 5:** Results for balance parameters (ANOVA with repeated measures on Time).

Measure	Main effect of Time	Main effect of Group	Group × Time interaction effect
<i>Static steady-state balance</i>			
Mod. Romberg Test (s)	< 0.001 [1.04]	< 0.001 [1.47]	< 0.001 [1.04]
Mod. Romberg Test (mm/s)	0.044 [0.49]	0.256 [0.45]	0.459 [0.36]
<i>Dynamic steady-state balance</i>			
Stride velocity (m/s)	0.001 [0.71]	0.204 [0.48]	0.006 [0.74]
Stride length (cm)	0.022 [0.53]	0.595 [0.27]	0.047 [0.60]
CV stride velocity (%)	0.830 [0.16]	0.098 [0.59]	0.001 [0.86]
CV stride length (%)	0.845 [0.11]	0.177 [0.51]	0.023 [0.65]
Stride velocity dual task (m/s)	0.002 [0.75]	0.095 [0.59]	0.281 [0.43]
Stride length dual task (cm)	0.035 [0.51]	0.445 [0.34]	0.533 [0.33]
CV stride velocity dual task (%)	0.263 [0.31]	0.509 [0.31]	0.369 [0.39]
CV stride length dual task (%)	0.01 [0.59]	0.368 [0.39]	0.442 [0.37]
<i>Proactive balance</i>			
TUG (s)	< 0.001 [1.26]	0.229 [0.47]	0.002 [0.82]
FRT (cm)	< 0.001 [0.93]	< 0.001 [1.65]	< 0.001 [1.31]
FRT (mm/s)	< 0.001 [1.32]	0.993 [0.03]	0.012 [0.69]
<i>Reactive balance</i>			
PRT (score)	Friedman: < 0.001 [ $\chi^2 = 50.96$ ]	Kruskal-Wallis: 0.012 [ $\chi^2 = 8.84$ ]	Kruskal-Wallis: pre-post: < 0.001 [ $\chi^2 = 24.41$ ] pre-follow-up: < 0.001 [ $\chi^2 = 17.38$ ]
Posturomed ML (cm)	< 0.001 [0.81]	0.615 [0.26]	0.096 [0.53]
Posturomed AP (cm)	0.081 [0.43]	0.621 [0.26]	0.280 [0.42]

Data indicate  $p$  values [Cohen's  $d$ ].  $AP$  = anterior-posterior;  $CV$  = coefficient of variation;  $FRT$  = Functional Reach Test;  $ML$  = mediolateral;  $PRT$  = Push and Release Test;  $TUG$  = Timed Up and Go Test

#### *Proactive balance*

Group × Time interaction reached the level of significance for the TUG ( $d = 0.82$ ). Post-hoc tests revealed a significant reduction in time needed to complete the test for the SUP from pre to post ( $d = 0.85$ ) and from pre to follow-up ( $d = 0.88$ ). No significant improvements were

found for UNSUP from pre to post ( $d = 0.44$ ), but from pre to follow-up ( $d = 0.63$ ). No statistically significant performance changes were found for CG (pre–post:  $d = 0.16$ ; pre–follow-up:  $d = 0.19$ ). Additionally, none of the experimental groups changed performance significantly from post to follow-up.

For the FRT, our analysis revealed a significant Group  $\times$  Time interaction for reach distance ( $d = 1.31$ ). SUP and UNSUP significantly increased their reach distance from pre to post (SUP:  $d = 1.82$ ; UNSUP:  $d = 0.65$ ) and from pre to follow-up (SUP:  $d = 1.65$ ; UNSUP:  $d = 0.79$ ). No significant changes were detected for CG (pre–post:  $d = -0.18$ ; pre–follow-up:  $d = -0.48$ ). From post to follow-up, no significant performance changes were found for all groups.

#### *Reactive balance*

Given that PRT scores are ordinal, nonparametrical Kruskal-Wallis Tests were applied. Therefore, delta values (post – pre, follow-up – pre, follow-up – post) were computed. Our statistical analyses revealed significant differences between groups from pre to post ( $\chi^2 = 24.41$ ), as well as from pre to follow-up ( $\chi^2 = 17.38$ ). No differences were found for post to follow-up changes ( $\chi^2 = 3.58$ ). Wilcoxon Tests yielded significant improvements for SUP and UNSUP from pre to post (SUP:  $PS_{dep} = 0.98$ ; UNSUP:  $PS_{dep} = 0.95$ ) and from pre to follow-up (SUP:  $PS_{dep} = 0.95$ ; UNSUP:  $PS_{dep} = 0.84$ ), whereas the CG did not change significantly (pre–post:  $PS_{dep} = 0.58$ ; pre–follow-up:  $PS_{dep} = 0.66$ ).

For the perturbation impulse on the Posturomed, no significant Group  $\times$  Time interactions were found (ML:  $d = 0.53$ ; AP:  $d = 0.42$ ).

#### *Lower extremity muscle power*

For the CST, the analysis showed significant Group  $\times$  Time interactions (rise time:  $d = 1.66$ ;  $P_{max}$ :  $d = 1.40$ ). Post-hoc analyses revealed significant improvements for the SUP from pre to post (reduction in rise time:  $d = 1.61$ ; enhancement in  $P_{max}$ :  $d = 1.12$ ) and from pre to follow-up testing (rise time:  $d = 1.55$ ;  $P_{max}$ :  $d = 0.99$ ). Significant improvements were found also for UNSUP from pre to post (rise time:  $d = 0.84$ ;  $P_{max}$ :  $d = 0.71$ ) and from pre to follow-up (rise time:  $d = 1.01$ ;  $P_{max}$ :  $d = 0.59$ ). The CG did not change significantly from pre to post (rise time:  $d = -0.09$ ;  $P_{max}$ :  $d = -0.01$ ) and pre to follow-up (rise time:  $d = 0.05$ ;  $P_{max}$ :  $d = -0.01$ ). From post to follow-up, no significant changes were observed for any of the experimental groups.



For the parameters total time and power in the SAT, significant Group  $\times$  Time interactions were computed (total time:  $d = 0.99$ ; power:  $d = 0.96$ ). Post-hoc analyses revealed significant improvements for SUP from pre to post (reduction of total time:  $d = 1.69$ ; enhancement of power:  $d = 1.81$ ) and from pre to follow-up (total time:  $d = 1.83$ ; power:  $d = 2.04$ ). Significant improvements also occurred for UNSUP from pre to post (total time:  $d = 0.82$ ; power:  $d = 0.97$ ) and from pre to follow-up (total time:  $d = 0.89$ ; power:  $d = 1.16$ ). Additionally, the CG significantly enhanced performance from pre to post (total time:  $d = 0.58$ ; power:  $d = 0.60$ ) and pre to follow-up (total time:  $d = 0.97$ ; power:  $d = 1.05$ ). From post to follow-up, none of the groups changed performance significantly.

Significant Group  $\times$  Time interactions were observed for both parameters in the SDT (total time:  $d = 1.02$ ; power:  $d = 1.07$ ). In the post-hoc tests, SUP significantly improved from pre to post (total time:  $d = 1.76$ ; power:  $d = 2.86$ ) and pre to follow-up (total time:  $d = 1.76$ ; power:  $d = 2.82$ ). Similarly, UNSUP significantly improved from pre to post ( $d = 1.75$ ; power:  $d = 2.30$ ) and from pre to follow-up (total time:  $d = 2.08$ ; power:  $d = 2.74$ ). The CG did not enhance performance significantly from pre to post (total time:  $d = 0.42$ ; power:  $d = 0.42$ ), but from pre to follow-up (total time:  $d = 0.56$ ; power:  $d = 0.58$ ). No significant changes were found from post to follow-up testing.

**Table 6:** Results for power parameters (ANOVA with repeated measures on Time).

Measure	Main effect of Time	Main effect of Group	Group $\times$ Time interaction effect
<i>Lower extremity power</i>			
CST (s)	< 0.001 [0.81]	< 0.001 [1.96]	< 0.001 [1.66]
CST (W/kg)	< 0.001 [1.74]	0.828 [0.17]	< 0.001 [1.40]
SAT (s)	< 0.001 [1.05]	< 0.001 [1.40]	< 0.001 [0.99]
SAT (W/kg)	< 0.001 [1.01]	< 0.001 [1.40]	< 0.001 [0.96]
SDT (s)	< 0.001 [1.04]	< 0.001 [1.54]	< 0.001 [1.02]
SDT (W/kg)	0.001 [0.72]	< 0.001 [1.72]	< 0.001 [1.07]

Data indicate  $p$  values [Cohen's  $d$ ]. *CST* = Chair Stand Test; *SAT* = Stair Ascent Test; *SDT* = Stair Descent Test

### *Body composition*

Group  $\times$  Time interaction turned out to be significant for lean tissue mass of the legs ( $d = 0.61$ ). Post-hoc tests showed no significant changes in SUP and CG. UNSUP significantly decreased lean tissue mass of the legs from pre to post ( $d = 0.08$ ), but not from pre to follow-up ( $d = 0.04$ ). No significant Group  $\times$  Time interactions were detected for other body composition parameters (i.e., total body water, total skeletal muscle mass).

### *Questionnaires*

No significant Group  $\times$  Time interactions were found for FES-I and QoL (Kruskal-Wallis Tests), as well as for DSST (ANOVA).

## **Discussion**

This is the first study that evaluated the effects of a CRT in healthy older adults on measures of balance, lower extremity muscle power, body composition, falls efficacy, cognitive function, and quality of life in a SUP vs. an UNSUP group. The main findings can be summarized as follows: (1) 12 weeks of CRT proved to be safe (i.e., no training or test-related injuries) and feasible with high attendance rates (92 % and 97 %) and low drop-out rates (SUP: 5 %, UNSUP: 14 %, CG: 9 %); (2) CRT was effective and resulted in significant improvements in intrinsic fall risk factors [i.e., primary outcomes: static steady-state balance (ROM), dynamic steady-state balance (stride velocity, CVs), proactive balance (TUG, FRT), reactive balance (PRT) and lower extremity muscle power (CST, SAT, SDT)]; (3) CRT failed to improve spatio-temporal gait parameters during dual task walking and the ability to compensate for ML perturbation impulses; (4) the SUP group showed larger effects in most investigated variables compared to UNSUP; (5) after 12 weeks of detraining, most balance and power variables were robust and remained above baseline values.

### *Effects of the CRT program on balance and muscle power*

Our hypothesis that CRT results in significant improvements in balance and muscle power was confirmed. For all primary outcome parameters, significant Group  $\times$  Time interactions in favor of the training groups were found. Significant performance enhancements from pre to post (post-hoc) in the training groups showed effects of  $0.62 \leq d \leq 1.82$  (6-68 %) for balance outcomes and  $0.71 \leq d \leq 2.86$  (12-29 %) for lower extremity power outcomes. These balance and power improvements are similar to those reported in the literature following a CRT. For

example, Park, Kim, Komatsu, Park, and Mutoh (2008) investigated the impact of a 48-week (three times per week) CRT with 65- to 70-year-olds on measures of static/dynamic steady-state balance. Following training, the IG showed significant improvements compared to a CG with regards to CoF displacements (post-hoc test:  $d = 2.03$ ), one-leg standing time (post-hoc test:  $d = 1.06$ ), and 10-meter rapid walking time (post-hoc test:  $d = 1.35$ ). No differences were observed for maximal step length, which is in line with our findings for habitual stride length. In another study, Suzuki, Kim, Yoshida, and Ishizaki (2004) performed a 6-month exercise intervention (supervised once every two weeks) with unsupervised exercises three times weekly in elderly adults ( $> 73$  years). After training, the IG significantly improved performance for steps in tandem gait ( $d = 0.54$ ) and the FRT ( $d = 1.01$ ), whereas the CG did not improve significantly. In line with our approach, Zhuang, Huang, Wu, and Zhang (2014) evaluated the effects of a 12-week supervised CRT (three times per week) in older adults (60-80 years) compared to a CG on measures of balance and leg strength. Significant improvements in favor of the IG were found for spatio-temporal gait parameters (post-hoc test:  $d = 0.59-1.06$ ), the TUG (post-hoc test:  $d = 0.73$ ), isometric strength of leg muscles (i.e., knee flexor/extensor, ankle dorsiflexor/plantarflexor; post-hoc test:  $d = 0.80-1.12$ ), and the 30-second CST (post-hoc test:  $d = 2.05$ ). Additionally, after a 6-month multimodal exercise program (three times weekly) including strength and balance exercises for older adults ( $67 \pm 6$  years), Gianoudis et al. (2014) found significant gains compared to a CG in the 30-second Sit to Stand Test (gain for IG: 11 %, gain in the CST in our study: 19 %) and the Timed Stair Climb (IG: 5 %; our study: 10 %). The underlying neuromuscular mechanisms responsible for performance enhancements cannot clearly be elucidated with our experimental approach. Since lean tissue mass of the legs and total skeletal muscle mass did not significantly increase in SUP and UNSUP, neural adaptations [i.e., increased activation of prime movers, improved coactivation of synergists, reduced coactivation of antagonists (Haekkinen, 2003)] appear to be a likely agent for the observed significant improvements in lower extremity strength/power.

Our program did not influence gait performance under dual task conditions. Training programs that specifically aim at improving balance under dual task conditions seem to have effects (Silsupadol et al., 2009). Thus, an explanation for absent effects could be an insufficient amount of exercises under dual task conditions. Of note, this study examined intrinsic risk factors for falls and not number of falls or fall rate. Since CST, SAT, and SDT were improved above limits which mark an increased fall risk in both SUP and UNSUP (limits: CST  $\geq 12$  s;

SAT/SDT  $\geq 5$  s) and SUP additionally improved above the limit in ROM (10-19 s) (Granacher et al., 2014), our program still could be a helpful tool for fall prevention.

### *Effects of supervision*

The hypothesis that the SUP group shows larger enhancements as compared to the UNSUP group was correct for most of the variables. This is partly in accordance with previous studies investigating a CRT in older adults (Cyarto et al., 2008; Donat & Oezcan, 2007; Wu et al., 2010). For example, Donat and Oezcan (2007) investigated the effects of an 8-week (three times per week) combined balance/strength/flexibility training in a SUP vs. an UNSUP group on balance, trunk flexibility, position sense of the knee joint and isometric leg extensor strength in elderly ( $> 65$  years). Training resulted in significant improvements in one-leg standing time, tandem standing time, Berg Balance Scale scores, trunk flexibility, and TUG in both groups, whereas leg strength and knee position sense only improved in the SUP group (all  $p < 0.05$ ). However, no inactive CG was involved and no interaction effects were computed, which is why findings have to be interpreted with caution. In the present study, the UNSUP group mainly improved in the proxies of leg power. This can be most likely explained by the high training intensity, which showed to evoke large improvements in previous studies (Fiatarone et al., 1990). In another study, Cyarto et al. (2008) reported that a 20-week (twice weekly) CRT in elderly (65-96 years) significantly improved static balance (one-leg standing time) in a SUP group compared to an UNSUP group (interaction effect:  $p = 0.05$ ). Performance in other balance measures (e.g., Up and Go Test) did not change significantly between groups, although tendencies were observed in favor of the SUP group. A limitation of the study of Cyarto and colleagues is that the UNSUP group received nine home visits by a coach which could have biased their findings. Finally, Wu et al. (2010) reported that 15 weeks of supervised tai chi vs. unsupervised tai chi exercises did not cause significant interaction effects for one-leg standing time and TUG, but for body sway in quiet stance with eyes open in favor of the SUP group (post-hoc test SUP group:  $d = 0.48$ ).

In summary, previous studies (Cyarto et al., 2008; Donat & Oezcan, 2007; Wu et al., 2010) found tendencies indicating that supervised training is more effective as compared to unsupervised training, but not to the extent of our study. An explanation for larger effects of SUP compared to UNSUP in our study could be a higher quality in the execution of exercises due to supervision. In fact, evaluation of the exercise diaries revealed similar mean stages of progression between groups. This implies that a higher rate of exertion and consequently a larger

adaptation was achieved in the SUP group. Especially the selection of an appropriate line of progression during balance training may have influenced the outcomes of the UNSUP group. In our study, UNSUP mainly improved in power variables. In strength/power training exercises, perceived intensity is easier to control, since the Borg scale was developed to detect perceived exertion rather than a perceived difficulty level. Participants of UNSUP may have exercised below an effective threshold to elucidate adaptations regarding balance. The question remains as to why UNSUP improved performance in the FRT and the PRT. Joshua and colleagues (2014) demonstrated that resistance training is more effective compared to balance training in improving performance in the FRT. Thus, the observed improvements may partially be explained by gains in strength/power. It is possible that a higher dose needs to be applied in order to improve all dimensions of balance-related fall risk factors in unsupervised programs, where a high perceived intensity cannot be ensured due to its uncontrolled character.

#### *Detraining effects*

As hypothesized, training-related improvements remained above baseline values for most of the variables. Regarding balance performance, only few studies investigated detraining effects in older adults after a CRT. Seco et al. (2013) reported that after a 9-month CRT and a 3-month detraining period, participants in the IG (65-74 years) were able to maintain balance (i.e., postural sway) from pre to follow-up. Participants older than 75 years were not able to maintain the improved level. Consequently, age may have an impact on detraining effects. Several previous studies examined detraining effects on strength/power variables in elderly persons (Carvalho et al., 2009; Helbostad et al., 2004; Seco et al., 2013). For example, Carvalho et al. (2009) investigated detraining effects after an 8-month multicomponent training (balance/strength/endurance exercises) in older women. After 12 weeks of detraining, performance improvements in the IG remained significantly above baseline value for 30-second CST, whereas the CG did not significantly improve. In summary, results regarding detraining effects in older adults are heterogeneous.

This is the first RCT that proved the effectiveness of a CRT in healthy older adults on balance and lower extremity power performance in a SUP vs. an UNSUP group and an inactive CG. Based on the high adherence rates, low dropout rates and no training-related injuries, our training program seems safe and may therefore be implemented into clinical practice to mitigate important intrinsic fall risk factors in healthy older adults. Given the larger effects of the

SUP as compared to the UNSUP group in most of the tested variables, we recommend training with at least three sessions per week with two being supervised by professional staff. Although performance enhancements showed to be relatively stable over a 12-week period, it is suggested that CRT should be conducted permanently to avoid performance decrements after training.

This study has a few limitations. First, the assessor was not blinded for group allocation. However, to minimize bias, the assessor strictly adhered to a predefined test protocol and gave the same instructions to every participant without any feedback on performance. Second, this study cannot illustrate possible adaptations in the central nervous and the neuromuscular system due to methodological constraints (e.g., no electrophysiological tests or imaging techniques). Third, our study findings cannot be generalized to less active or even sedentary cohorts because the examined population was classified as physically active. Future studies should evaluate the program in high-risk populations (e.g., institutionalized persons).

## References

- Agrawal, Y., Carey, J. P., Hoffman, H. J., Sklare, D. A., & Schubert, M. C. (2011). The modified Romberg Balance Test: normative data in U.S. adults. *Otology & neurotology : official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology*, 32(8), 1309–1311. <https://doi.org/10.1097/MAO.0b013e31822e5bee>
- Anderson, L. J., Erceg, D. N., & Schroeder, E. T. (2012). Utility of multifrequency bioelectrical impedance compared with dual-energy x-ray absorptiometry for assessment of total and regional body composition varies between men and women. *Nutrition Research*, 32(7), 479–485. <https://doi.org/10.1016/j.nutres.2012.05.009>
- Bean, J. F., Kiely, D. K., LaRose, S., Alian, J., & Frontera, W. R. (2007). Is stair climb power a clinically relevant measure of leg power impairments in at-risk older adults? *Archives of Physical Medicine & Rehabilitation*, 88(5), 604–609. <https://doi.org/10.1016/j.apmr.2007.02.004>
- Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine and science in sports and exercise*, 14(5), 377–381.
- Carvalho, M. J., Marques, E., & Mota, J. (2009). Training and detraining effects on functional fitness after a multicomponent training in older women. *Gerontology*, 55(1), 41–48. <https://doi.org/10.1159/000140681>
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. London: Routledge Academic.
- Cohen-Mansfield, J., S Marx, M., & Guralnik, J. M. (2003). Motivators and Barriers to Exercise in an Older Community-Dwelling Population. *Journal of Aging & Physical Activity*, 11(2), 242–253.
- Csuka, M., & McCarty, D. J. (1985). Simple method for measurement of lower extremity muscle strength. *The American journal of medicine*, 78(1), 77–81.
- Cyarto, E. V., Brown, W. J., Marshall, A. L., & Trost, S. G. (2008). Comparative effects of home- and group-based exercise on balance confidence and balance ability in older adults: cluster randomized trial. *Gerontology*, 54(5), 272–280. <https://doi.org/10.1159/000155653>

- Donat, H., & Oezcan, A. (2007). Comparison of the effectiveness of two programmes on older adults at risk of falling: unsupervised home exercise and supervised group exercise. *Clinical rehabilitation*, *21*(3), 273–283. <https://doi.org/10.1177/0269215506069486>
- Duncan, P. W., Weiner, D. K., Chandler, J., & Studenski, S. (1990). Functional reach: a new clinical measure of balance. *Journal of gerontology*, *45*(6), M192-7.
- Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G\*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods*, *39*(2), 175–191.
- Fiatarone, M. A., Marks, E. C., Ryan, N. D., Meredith, C. N., Lipsitz, L. A., & Evans, W. J. (1990). High-intensity strength training in nonagenarians. Effects on skeletal muscle. *Journal of the American Medical Association*, *263*(22), 3029–3034.
- Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). “Mini-mental state”. A practical method for grading the cognitive state of patients for the clinician. *Journal of psychiatric research*, *12*(3), 189–198.
- Franco, M. R., Howard, K., Sherrington, C., Ferreira, P. H., Rose, J., Gomes, J. L., & Ferreira, M. L. (2015). Eliciting older people’s preferences for exercise programs: a best-worst scaling choice experiment. *Journal of Physiotherapy*, *61*(1), 34–41. <https://doi.org/10.1016/j.jphys.2014.11.001>
- Gianoudis, J., Bailey, C. A., Ebeling, P. R., Nowson, C. A., Sanders, K. M., Hill, K., & Daly, R. M. (2014). Effects of a targeted multimodal exercise program incorporating high-speed power training on falls and fracture risk factors in older adults: a community-based randomized controlled trial. *Journal of Bone and Mineral Research*, *29*(1), 182–191. <https://doi.org/10.1002/jbmr.2014>
- Gillespie, L. D., Robertson, M. C., Gillespie, W. J., Sherrington, C., Gates, S., Clemson, L. M., & Lamb, S. E. (2012). Interventions for preventing falls in older people living in the community. *The Cochrane database of systematic reviews*, *9*, CD007146. doi: 10.1002/14651858.CD007146.pub3
- Granacher, U., Muehlbauer, T., Gschwind, Y. J., Pfenninger, B., & Kressig, R. W. (2014). Assessment and training of strength and balance for fall prevention in the elderly: recommendations of an interdisciplinary expert panel. *Zeitschrift für Gerontologie und Geriatrie*, *47*(6), 513–526. <https://doi.org/10.1007/s00391-013-0509-5>
- Granacher, U., Wick, C., Rueck, N., Esposito, C., Roth, R., & Zahner, L. (2011). Promoting balance and strength in the middle-aged workforce. *International Journal of Sports Medicine*, *32*(1), 35–44. <https://doi.org/10.1055/s-0030-1267214>
- Granacher, U., Zahner, L., & Gollhofer, A. (2008). Strength, power, and postural control in seniors: Considerations for functional adaptations and for fall prevention. *European Journal of Sport Science*, *8*(6), 325–340.
- Grissom, R. J., & Kim, J. J. (2012). *Effect sizes for research: Univariate and multivariate applications*. London: Routledge.
- Gschwind, Y. J., Kressig, R. W., Lacroix, A., Muehlbauer, T., Pfenninger, B., & Granacher, U. (2013). A best practice fall prevention exercise program to improve balance, strength / power, and psychosocial health in older adults: study protocol for a randomized controlled trial. *BMC geriatrics*, *13*, 105. <https://doi.org/10.1186/1471-2318-13-105>
- Haekkinen, K. (2003). Ageing and neuromuscular adaptation to strength training. In P. V. Komi (Ed.), *Strength and Power in Sport* (pp. 409–425). Oxford, UK: Blackwell Science Ltd.

- Helbostad, J. L., Sletvold, O., & Moe-Nilssen, R. (2004). Effects of home exercises and group training on functional abilities in home-dwelling older persons with mobility and balance problems. A randomized study. *Ageing clinical and experimental research*, *16*(2), 113–121.
- Jacobs, J. V., Horak, F. B., van Tran, K., & Nutt, J. G. (2006). An alternative clinical postural stability test for patients with Parkinson's disease. *Journal of neurology*, *253*(11), 1404–1413. <https://doi.org/10.1007/s00415-006-0224-x>
- Joshua, A. M., D'Souza, V., Unnikrishnan, B., Mithra, P., Kamath, A., Acharya, V., & Venugopal, A. (2014). Effectiveness of progressive resistance strength training versus traditional balance exercise in improving balance among the elderly - a randomised controlled trial. *Journal of clinical and diagnostic research: JCDR*, *8*(3), 98–102. <https://doi.org/10.7860/JCDR/2014/8217.4119>
- Lee, M. M., Song, C. H., Lee, K. J., Jung, S. W., Shin, D. C., & Shin, S. H. (2014). Concurrent Validity and Test-retest Reliability of the OPTOGait Photoelectric Cell System for the Assessment of Spatio-temporal Parameters of the Gait of Young Adults. *Journal of Physical Therapy Science*, *26*(1), 81–85. <https://doi.org/10.1589/jpts.26.81>
- Leonhart, R. (2004). [Estimating effect sizes in clinical trials]. *Die Rehabilitation*, *43*(4), 241–246. <https://doi.org/10.1055/s-2004-828293>
- Lienhard, K., Schneider, D., & Maffioletti, N. A. (2013). Validity of the Optogait photoelectric system for the assessment of spatiotemporal gait parameters. *Medical engineering & physics*, *35*(4), 500–504. <https://doi.org/10.1016/j.medengphy.2012.06.015>
- Liu, C.-J., & Latham, N. K. (2009). Progressive resistance strength training for improving physical function in older adults. *The Cochrane database of systematic reviews*. (3), CD002759. <https://doi.org/10.1002/14651858.CD002759.pub2>
- Mueller, O., Gunther, M., Krauss, I., & Horstmann, T. (2004). [Physical characterization of the therapeutic device Posturomed as a measuring device—presentation of a procedure to characterize balancing ability]. *Biomedizinische Technik. Biomedical engineering*, *49*(3), 56–60. <https://doi.org/10.1515/BMT.2004.011>
- Newton, R. A. (2001). Validity of the multi-directional reach test: a practical measure for limits of stability in older adults. *The journals of gerontology. Series A, Biological sciences and medical sciences*, *56*(4), M248-52.
- Park, H., Kim, K. J., Komatsu, T., Park, S. K., & Mutoh, Y. (2008). Effect of combined exercise training on bone, body balance, and gait ability: a randomized controlled study in community-dwelling elderly women. *Journal of bone and mineral metabolism*, *26*(3), 254–259. <https://doi.org/10.1007/s00774-007-0819-z>
- Podsiadlo, D., & Richardson, S. (1991). The timed “Up & Go”: a test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society*, *39*(2), 142–148.
- Rapp, K., Freiberger, E., Todd, C., Klenk, J., Becker, C., Denkinger, M., . . . Fuchs, J. (2014). Fall incidence in Germany: results of two population-based studies, and comparison of retrospective and prospective falls data collection methods. *BMC geriatrics*, *14*, 105. <https://doi.org/10.1186/1471-2318-14-105>
- Rubenstein, L. Z. (2006). Falls in older people: epidemiology, risk factors and strategies for prevention. *Age and Ageing*, *35* Suppl 2, ii37-ii41. <https://doi.org/10.1093/ageing/afl084>
- Schott, N., & Kurz, A.-K. (2008). Falls in older adults: risk factors assessment prevention. A review. *Zeitschrift für Sportpsychologie*, *15*(2), 45–62.



- Seco, J., Abecia, L. C., Echevarria, E., Barbero, I., Torres-Unda, J., Rodriguez, V., & Calvo, J. I. (2013). A long-term physical activity training program increases strength and flexibility, and improves balance in older adults. *Rehabilitation Nursing, 38*(1), 37–47. <https://doi.org/10.1002/rnj.64>
- Silsupadol, P., Shumway-Cook, A., Lugade, V., van Donkelaar, P., Chou, L. S., Mayr, U., & Woollacott, M. H. (2009). Effects of single-task versus dual-task training on balance performance in older adults: a double-blind, randomized controlled trial. *Archives of Physical Medicine and Rehabilitation, 90*(3), 381–387. <https://doi.org/10.1016/j.apmr.2008.09.559>
- Suzuki, T., Kim, H., Yoshida, H., & Ishizaki, T. (2004). Randomized controlled trial of exercise intervention for the prevention of falls in community-dwelling elderly Japanese women. *Journal of Bone and Mineral Metabolism, 22*(6), 602–611. <https://doi.org/10.1007/s00774-004-0530-2>
- Thalman, B., Spiegel, R., Staehelin, H., Brubacher, D., Ermini-Fünfschilling, D., Blaesi, S., & Monsch, A. U. (2002). Dementia screening in general practice: optimised scoring for the Clock Drawing Test. *Brain aging, 2*(2), 36–43.
- Tiedemann, A., Shimada, H., Sherrington, C., Murray, S., & Lord, S. (2008). The comparative ability of eight functional mobility tests for predicting falls in community-dwelling older people. *Age and Ageing, 37*(4), 430–435. <https://doi.org/10.1093/ageing/afn100>
- Tinetti, M. E. (2003). Clinical practice. Preventing falls in elderly persons. *The New England Journal of Medicine, 348*(1), 42–49. <https://doi.org/10.1056/NEJMcp020719>
- Tuunainen, E., Rasku, J., Jäntti, P., Moisiio-Vilenius, P., Mäkinen, E., Toppila, E., & Pyykkö, I. (2013). Postural stability and quality of life after guided and self-training among older adults residing in an institutional setting. *Clinical interventions in aging, 8*, 1237–1246. <https://doi.org/10.2147/CIA.S47690>
- Wu, G., Keyes, L., Callas, P., Ren, X., & Bookchin, B. (2010). Comparison of telecommunication, community, and home-based Tai Chi exercise programs on compliance and effectiveness in elders at risk for falls. *Archives of Physical Medicine and Rehabilitation, 91*(6), 849–856. <https://doi.org/10.1016/j.apmr.2010.01.024>
- Zhuang, J., Huang, L., Wu, Y., & Zhang, Y. (2014). The effectiveness of a combined exercise intervention on physical fitness factors related to falls in community-dwelling older adults. *Clinical interventions in aging, 9*, 131–140. <https://doi.org/10.2147/CIA.S56682>

**Publication IV****EFFECTS OF SUPERVISED VERSUS UNSUPERVISED TRAINING PROGRAMS ON BALANCE AND MUSCLE STRENGTH IN OLDER ADULTS: A SYSTEMATIC REVIEW AND META-ANALYSIS**

André Lacroix<sup>1,2</sup>, Tibor Hortobágyi<sup>3</sup>, Rainer Beurskens<sup>1,2</sup> & Urs Granacher<sup>1</sup>

<sup>1</sup> Division of Training and Movement Science, University of Potsdam, Potsdam, Germany

<sup>2</sup> Department of Geriatric Research, Agaplesion Bethanien Hospital gGmbH, Geriatric Center at the University of Heidelberg, Heidelberg, Germany

<sup>3</sup> Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands

**Reference**

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## Abstract

### *Background*

Balance (BT) and resistance training (RT) can improve healthy older adults' balance and muscle strength. Delivering such exercise programs at home without supervision may facilitate participation for older adults because they do not have to leave their homes. So far, no systematic literature analysis has been conducted to determine if supervision affects the effectiveness of these programs to improve healthy older adults' balance and muscle strength/power.

### *Objectives*

The objective of this systematic review and meta-analysis was to quantify the effectiveness of supervised versus unsupervised BT and/or RT programs on measures of balance and muscle strength/power in healthy older adults. In addition, the impact of supervision on training-induced adaptive processes was evaluated in the form of dose-response relationships by analyzing randomized controlled trials that compared supervised with unsupervised trials.

### *Data Sources*

A computerized systematic literature search was performed in the electronic databases PubMed, Web of Science, and SportDiscus to detect articles examining the role of supervision in BT and/or RT in older adults.

### *Study Eligibility Criteria*

The initially identified 6,041 articles were systematically screened. Studies were included if they examined BT and/or RT in adults aged  $\geq 65$  with no relevant diseases and registered at least one behavioral balance (e.g., time during single leg stance) and/or muscle strength/power outcome (e.g., time for 5 Times Chair Rise Test). Finally, 11 studies were eligible for inclusion in this meta-analysis.

### *Study Appraisal*

Weighted mean standardized mean differences between subjects (SMD<sub>bs</sub>) of supervised versus unsupervised BT/RT studies were calculated. The included studies were coded for the following variables: number of participants, sex, age, number and type of interventions, type

of balance/strength tests, and change (%) from pre- to post-intervention values. Additionally, we coded training according to the following modalities: period, frequency, volume, modalities of supervision (i.e., number of supervised/unsupervised sessions within the supervised or unsupervised training groups, respectively). Heterogeneity was computed using  $I^2$  and  $\chi^2$  statistics. The methodological quality of the included studies was evaluated using the Physiotherapy Evidence Database (PEDro) scale.

### *Results*

Our analyses revealed that in older adults, supervised BT/RT was superior compared with unsupervised BT/RT in improving measures of static steady-state (mean  $SMD_{bs} = 0.28$ ,  $p = 0.39$ ), dynamic steady-state (mean  $SMD_{bs} = 0.35$ ,  $p = 0.02$ ), proactive balance (mean  $SMD_{bs} = 0.24$ ,  $p = 0.05$ ), balance test batteries (mean  $SMD_{bs} = 0.53$ ,  $p = 0.02$ ), and measures of muscle strength/power (mean  $SMD_{bs} = 0.51$ ,  $p = 0.04$ ). Regarding the examined dose-response relationships, our analyses showed that a number of 10-29 additional supervised sessions in the supervised training groups compared with the unsupervised training groups resulted in the largest effects for static steady-state balance (mean  $SMD_{bs} = 0.35$ ), dynamic steady-state balance (mean  $SMD_{bs} = 0.37$ ), and muscle strength/power (mean  $SMD_{bs} = 1.12$ ). Further,  $\geq 30$  additional supervised sessions in the supervised training groups were needed to produce the largest effects on proactive balance (mean  $SMD_{bs} = 0.30$ ) and balance test batteries (mean  $SMD_{bs} = 0.77$ ). Effects in favor of supervised programs were larger for studies that did not include any supervised sessions in their unsupervised programs (mean  $SMD_{bs}$ : 0.28-1.24) compared with studies that implemented a few supervised sessions in their unsupervised programs (e.g., three supervised sessions throughout the entire intervention program;  $SMD_{bs}$ : -0.06-0.41).

### *Limitations*

The present findings have to be interpreted with caution because of the low number of eligible studies and the moderate methodological quality of the included studies which is indicated by a median PEDro score of 5. Furthermore, we indirectly compared dose-response relationships across studies and not from single controlled studies.

### *Conclusions*

Our analyses suggest that supervised BT and/or RT improved measures of balance and muscle strength/power to a greater extent than unsupervised programs in older adults. Due to the small number of available studies, we were unable to establish a clear dose-response relationship with regards to the impact of supervision. However, the positive effects of supervised training are particularly prominent when compared with completely unsupervised training programs. It is therefore recommended to include supervised sessions (i.e., two out of three sessions/week) in BT/RT programs to effectively improve balance and muscle strength/power in older adults.

**Keywords:** balance training; resistance training; supervised/unsupervised training; elderly

### *Key points*

The present systematic review and meta-analysis quantified the effects of supervised versus unsupervised balance and/or resistance training on measures of balance and muscle strength/power in older adults. Additionally, dose-response relationships on the effects of supervision were quantified.

Supervised compared with unsupervised exercise interventions proved to induce larger effects in measures of balance and muscle strength/power in older adults. Even small amounts of supervised sessions within mainly unsupervised interventions seem to have a beneficial extra effect.

This study provides preliminary evidence for practitioners and therapists on the effects and dose-response relations of exercise supervision to increase the efficacy of balance and resistance training in healthy older adults.

## Introduction

Biological aging and physical inactivity contribute to the degenerative processes in the muscular (e.g., loss of type II muscle fibers) and the neural system (e.g., loss of sensory and motor neurons) (Aagaard, Suetta, Caserotti, Magnusson, & Kjaer, 2010). These physiological deteriorations result in impaired static/dynamic balance and muscle strength/power in older adults (Abrahamova & Hlavacka, 2008; Bohannon & Williams Andrews, 2011; Manini & Clark, 2012). For example, older adults' compared with young adults' static steady-state balance [i.e., single leg stance (SLS)] (Springer, Marin, Cyhan, Roberts, & Gill, 2007), dynamic steady-state balance (i.e., habitual walking speed) (Granacher, Muehlbauer, Bridenbaugh, Wehrle, & Kressig, 2010), proactive balance [i.e., Timed-Up-and-Go-Test (TUG)] (Bohannon, 2006), reactive balance (i.e., functional reflex activity) (Granacher, Gruber, & Gollhofer, 2010), balance test battery [i.e., Berg Balance Scale (BBS)] (Steffen, Hacker, & Mollinger, 2002), and muscle power [i.e., 5 Times Chair Rise Test (5CRT)] performance are significantly lower (Lusardi, Pellecchia, & Schulman, 2003). For most of these tests, critical thresholds associated with an increased risk of falls were previously reported in the literature [for a review see Granacher, Muehlbauer, Gschwind, Pfenninger, and Kressig (2014)]. Falls pose a substantial personal burden and threaten the financial sustainability of health care systems (Sherrington et al., 2016). Fall-related injuries increase mobility disability, nursing home admission, and mortality (Gill, Allore, Holford, & Guo, 2004; Rubenstein, 2006; Sherrington et al., 2016; Tinetti, 2003). Decreases in lower extremity muscle strength/power and especially dynamic balance are also associated with mobility disability and mortality (Manini & Clark, 2012; van Kan et al., 2009). As the proportion of older adults is rising globally, there is a need for a widespread implementation of effective exercise programs to mitigate the age-related declines in static/dynamic balance and muscle strength/power.

Appropriately designed balance training (BT) and resistance training (RT) programs can improve even healthy older adults' static/dynamic balance (Gillespie et al., 2012; Hortobágyi et al., 2015; Howe, Rochester, Jackson, Banks, & Blair, 2007) and muscle strength/power (Christie, 2011; Granacher, Muehlbauer, Zahner, Gollhofer, & Kressig, 2011) with single vs. multifactorial exercise interventions appearing equally effective to prevent falls (Campbell & Robertson, 2007; Sherrington et al., 2016). However, there is much inconsistency in the results with respect to the programs being delivered with or without supervision in the form of supervised facility-based programs, unsupervised home-based programs, or a combination of both (Christie, 2011; Freiberger et al., 2013; Gillespie et al., 2012; Howe et al., 2007). Ad-

Addressing the inconsistencies are important in view of the recent hypothesis that group- and home-based training programs are equally effective to prevent falls (Sherrington et al., 2016). Evidence in support of such a prediction could perhaps increase the number of older adults participating in fall prevention programs delivered at home without supervision, as many older adults have no ability or motivation to participate in a supervised facility-based program (Cohen-Mansfield, Marx, & Guralnik, 2003). In particular, older adults with a history of falls seem to prefer exercise programs that can be conducted at home or require no transport (Franco et al., 2015). Reduced costs associated with no supervision could help popularize fall prevention exercise programs for large populations (Sherrington et al., 2016). While cost-effectiveness is an important issue, the physiological effectiveness of an exercise program relative to mobility, balance, and muscle strength/power is at least of the same significance.

Randomized controlled trials (RCTs) suggested greater effects of supervised versus unsupervised BT and/or RT programs in older adults (Cyarto, Brown, Marshall, & Trost, 2008a; Donat & Oezcan, 2007; Lacroix et al., 2016; Watson, Weeks, Weis, Horan, & Beck, 2015; Wu, Keyes, Callas, Ren, & Bookchin, 2010). However, a systematic comparison of the two delivery methods is lacking and a systematic review and meta-analysis could provide the most reliable evidence (Burns, Rohrich, & Chung, 2011). Previous reviews on this issue compared group and/or home-based interventions with inactive controls without directly comparing the underlying exercise effects. For example, individualized home-based exercise programs (partly supervised) increased physical activity, balance, mobility, and muscle strength (Hill, Hunter, Batchelor, Cavalheri, & Burton, 2015). Another review reported similar reductions in fall rates in older adults following group and home-based exercise programs relative to inactive controls (Gillespie et al., 2012). Other meta-analyses evaluated the effects of home- versus center-based physical activity programs in older adults suffering from severe diseases [i.e., cardiovascular diseases/ chronic obstructive pulmonary disorder (Ashworth, Chad, Harrison, Reeder, & Marshall, 2005); intermittent claudication (Fokkenrood et al., 2013); myocardial infarction, angina, heart failure or revascularization (Taylor et al., 2015)]. For example, home- and center-based forms of cardiac rehabilitation improved quality of life to a similar extent (Taylor et al., 2015). In contrast, center-based vs. home-based programs were superior if the goal was to improve walking distance and time to claudication in patients with peripheral vascular disease (Ashworth et al., 2005; Fokkenrood et al., 2013). Owing to the methodological limitations of previous systematic reviews and meta-analyses (i.e., indirect comparisons of supervised and unsupervised exercise programs) and heterogeneous results in

clinical populations, it seems appropriate and timely to conduct a meta-analysis on the effects of supervised versus unsupervised exercise interventions in healthy older adults. Additionally, no previous review determined the impact of supervision in the form of dose-response relations on balance and muscle strength/power outcomes in this population.

Taken together, the objective of the present systematic review and meta-analysis was to quantify the effects of supervised versus unsupervised BT and/or RT on measures of balance (static/dynamic steady-state balance, proactive balance, reactive balance, and balance test batteries) and measures of muscle strength/power (dynamic muscle strength and muscle power with isotonic muscle contractions) in healthy older adults. In addition, the impact of exercise supervision (i.e., number of additional supervised sessions in supervised training groups; presence or absence of supervised sessions in unsupervised training groups) was evaluated and characterized in the form of dose-response relationships. Of note, dose-response relationships are essential for providing evidence-based recommendations for therapists and practitioners. Based on the findings of single RCTs and meta-analyses in clinical populations, we hypothesized that supervised exercise programs are superior compared with unsupervised exercise programs for improving healthy older adults' balance and muscle strength/power.

## **Methods**

The present meta-analysis follows the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) (Liberati et al., 2009).

### *Literature search*

A computerized systematic literature search was performed in the databases PubMed, Web of Science, and SportDiscus using a Boolean search strategy with the operators AND, OR, NOT. To keep the search up to date, automatic weekly searches were applied until December 2016. The syntax consisted of three main terms based on the previously introduced search syntax by Lesinski et al. (2015). Term 1 focused on the age of participants, which involved the term "old" and its equivalents. Term 2 included the intervention term by focusing on different types of interventions and modalities of implementation: (1) "resistance training", (2) "balance training", (3) other forms like "dance training" or "tai chi", (4) combinations of different training forms, (5) "supervised training", and (6) "unsupervised training", including search term equivalents within each term. Term 3 comprised exclusion terms (e.g., "children", "patients"). We additionally applied the following filters: full text, human species, and ages: 65+



years. The PubMed search syntax was adapted to the Web of Science and SPORTDiscus databases. To identify additional studies suitable for inclusion, we examined the reference lists of relevant review articles [e.g., (Gillespie et al., 2012), (Hill et al., 2015)], as well as each potentially relevant article.

### *Selection criteria/study eligibility*

We followed the PICOS (participants, interventions, comparators, outcomes, and study design) approach (Liberati et al., 2009) and studies eligible for inclusion had to meet the following criteria: (1) population: subjects with a study mean age  $\geq 65$  years; (2) intervention: including a supervised RT, BT (comprising static/dynamic postural stabilization exercises; including walking, dancing, tai chi), or any combination of BT and RT; (3) comparator: including an unsupervised RT, BT (comprising static/dynamic postural stabilization exercises; including walking, dancing, tai chi), or any combination of BT and RT; (4) outcome: at least one measure of balance [i.e., static steady-state balance (e.g., time during single leg stance), dynamic steady-state balance (e.g., gait speed during the 10-m gait test), proactive balance (e.g., time to complete the Timed Up and Go Test), reactive balance (e.g., center of pressure displacements after an unexpected perturbation), balance test batteries (e.g., score in the Berg Balance scale)] and/or one clinical measure of muscle strength/power performance [i.e., dynamic muscle strength [e.g., repetitions in 30 seconds Chair Stand Test (30s CST)], dynamic muscle power (e.g., time for 5CRT)]; and (5) study design: RCTs. Studies were excluded, if they (1) examined cognitively limited and/or ill subjects. We deemed participants as ill, if relevant diseases (e.g., neurophysiological, cardiovascular, psychological, cancer, vestibular/gait disorder) were reported. Studies were still assessed if they included participants with limited performance in specific tests (i.e., leg extensor torque, Berg Balance Scale, Activities-Specific Balance Confidence Scale), a low bone mass, and a history of falls; (2) failed to report minimum requirements regarding training design such as volume, frequency, and modalities of supervision; (3) examined the effects of nutritional supplements in combination with training; (4) used an inactive control group only; and (5) did not report means and standard deviations in the results section or upon request.

For a clear distinction between supervised and unsupervised training groups, we applied a ratio dividing the number of supervised training sessions by the total number of training sessions for each study and training group. Referring to the most frequently implemented training frequency of three sessions per week (Granacher et al., 2011), we defined training groups

as supervised (SUP), if at least two out of three sessions were supervised (i.e., sessions were attended by an instructor supervising execution of exercises), corresponding to a ratio of  $\geq 0.67$ . Furthermore, a training group was declared unsupervised (UNSUP), if at least two of three sessions were unsupervised (i.e., sessions were not attended by an instructor), corresponding to a ratio of  $\leq 0.33$ . According to this classification, some training groups were classified as unsupervised, although they received a minimal dose of supervision. Studies were excluded, if cut-off ratios were not met. Table 1 shows the ratios for the supervised and unsupervised training groups of all included studies. Studies were screened for eligibility by two independent reviewers (AL, RB). In cases of disagreement, UG was consulted for clarification.

### *Coding of studies*

Each study was coded for the following variables: number of participants, sex, age, body mass, and height; number and type of interventions, type of balance/strength tests, and baseline and post-intervention values of relevant tests. Additionally, we coded training according to the following modalities: period, frequency, volume, modalities of supervision (i.e., number of supervised/unsupervised sessions within SUP or UNSUP). If data were missing or not reported clearly, missing information was requested from the authors. After completion of the literature search, six authors had to be contacted and all were helpful and replied.

According to Shumway-Cook and Woollacott (2007), balance control is highly task specific and has to be subdivided into different categories: static/dynamic steady-state balance (i.e., maintaining a stable position in sitting, standing, and walking), proactive balance (i.e., anticipation and accomplishment of a predicted disturbance), and reactive balance (i.e., compensation for an unexpected disturbance). Therefore, our analyses focused on different balance outcome categories: (1) static steady-state balance (e.g., time during SLS), (2) dynamic steady-state balance (e.g., gait speed during 10-m gait test), (3) proactive balance (e.g., time for TUG), (4) reactive balance (e.g., center of pressure displacements after an unexpected perturbation), and (5) balance test batteries. For the assessment of lower extremity muscle strength/power, we focused on clinical tests [i.e., dynamic muscle strength/power (e.g., 30s CST) and 5CRT)] as suggested by Granacher et al. (2014). If studies reported multiple variables within one of the outcome categories, only one representative outcome variable was used for further analysis. In the category static steady-state balance, the highest priority was given to the SLS with eyes opened. As a proxy for dynamic steady-state balance, gait speed was

used. The TUG was preferably selected as a proxy for proactive balance, and for reactive balance, we chose center of pressure (CoP) displacements following a perturbation impulse. The Berg Balance Scale was used as the most prominent balance test battery. For dynamic muscle strength/power testing, the highest priority was given to the accomplished time in the 5CRT. If a study used other tests, we decided to include those tests in our analyses that were most similar in terms of their temporal/spatial structure to the ones described above (e.g., gait speed in tandem walking).

Because of the limited number of studies that examined some of the different balance outcome categories (e.g., reactive balance, balance test batteries), we additionally quantified an overall balance performance outcome to facilitate a more comprehensive view, as proposed by Lesinski et al. (2015). Here, we included tests of different balance performance categories according to their usage in the respective studies. We applied a decision tree prioritizing the importance of the test to assess functional capacity: (1) balance test batteries, (2) dynamic steady-state balance, (3) reactive balance, (4) proactive balance, and (5) static steady-state balance.

#### *Data extraction*

The main study characteristics (i.e., cohort, sex, age, interventions, training modalities, relevant outcomes, baseline and post-values, standard deviations) of all included studies were stored in a separate Excel template.

#### *Assessment of methodological quality*

The methodological quality of the included studies was evaluated using the Physiotherapy Evidence Database (PEDro) scale (Maher, Sherrington, Herbert, Moseley, & Elkins, 2003). The PEDro scale consists of 11 items assessing the internal study validity and the presence of statistically replicable information of RCTs. Values range from 0 (low quality) to 10 (high quality) with a score of  $\geq 6$  representing the cut-off value for high-quality RCTs. Inter-rater reliability was shown to be fair to good (ICC = 0.68) (Maher et al., 2003).

**Table 1:** Ratio of supervised training sessions relative to the total number of training sessions in the included supervised and unsupervised training groups.

<b>References</b>	<b>Total number of sessions in supervised group</b>	<b>Total number of supervised sessions in supervised group</b>	<b>Ratio of the supervised group (supervised sessions / total number of sessions)</b>	<b>Total number of sessions in unsupervised group</b>	<b>Total number of supervised sessions in unsupervised group</b>	<b>Ratio of the unsupervised group (supervised sessions / total number of sessions)</b>
Almeida et al. (2013)	72	72	1.00	72	12	0.17
Boshuizen et al. (2005)	30	20	0.67	30	10	0.33
Cyarto et al. (2008a/b)	40	40	1.00	40	8	0.20
Donat & Oezcan (2007)	24	24	1.00	24	3	0.13
Hinman (2002)	12	12	1.00	12	0	0
Karahan et al. (2015)	30	30	1.00	30	0	0
Lacroix et al. (2016)	36	24	0.67	36	0	0
Lindemann et al. (2004)	16	16	1.00	16	2	0.13
Van Roie et al. (2010) / Opdenacker et al. (2011)	132	132	1.00	132	5	0.04
Watson et al. (2015)	70	70	1.00	70	0	0
Wu et al. (2010)	45	45	1.00	45	0	0
Mean	46.1	44.1	0.9	46.1	3.6	0.1

### *Statistical analyses*

To examine the effects of supervised compared with unsupervised BT and/or RT on measures of balance and muscle strength/power, we calculated within-subject standardized mean differences ( $SMD_{ws} = [\text{mean pre-value} - \text{mean post-value}] / \text{standard deviation pre-value}$ ) and between-subject standardized mean differences ( $SMD_{bs} = [\text{mean post-value intervention group} - \text{mean post-value control group}] / \text{pooled standard deviation}$ ). The  $SMD_{bs}$  was adjusted for sample size according to the formula:  $g = \left(1 - \frac{3}{4N_i - 9}\right)$ , where  $N_i$  is the total sample size of the intervention and control group (Hedges & Olkin, 1985). Studies were also weighted according

to the size of the standard error using the computer program Review Manager version 5.3 (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014) (Deeks & Higgins, 2010). We applied a random-effects meta-analysis model to compute the  $SMD_{bs}$  with 95 % confidence intervals (CIs) in Review Manager. Heterogeneity was evaluated using  $I^2$  and  $\chi^2$  statistics (Higgins, Thompson, Deeks, & Altman, 2003). SMDs were calculated for each pre-defined outcome category (i.e., static steady-state/dynamic steady-state/proactive/reactive balance, balance test batteries, dynamic muscle strength/power of lower extremities), if possible. Considering different outcome measures (i.e., gait speed vs. time for the 5CRT), SMD can be positive or negative. For a better understanding of the results, improvements of outcomes ( $SMD_{ws}$ ) and superiority of SUP compared with UNSUP ( $SMD_{bs}$ ) were reported using a positive  $SMD_{ws}/SMD_{bs}$ . The computed  $SMD_{ws}/SMD_{bs}$  allow a systematic and quantitative examination of the effects of supervised versus unsupervised training on measures of balance and muscle strength/power and they additionally help to determine, whether the detected differences are of practical concern. SMD values of 0.20 indicate small effects, values of 0.50 indicate medium effects, and values of 0.80 indicate large effects (Cohen, 1992). Furthermore, we examined dose-response relationships of exercise supervision (i.e., number of additional supervised sessions in SUP compared with UNSUP; presence/absence of supervised sessions in UNSUP). As a cut-off score for the number of additional supervised sessions in SUP, we computed the median of the values across the included studies (i.e., 30). To detect possible group differences in study quality, we calculated Mann-Whitney  $U$  and Kruskal-Wallis Tests.

## Results

Figure 1 shows the study selection flow chart.

### *Study characteristics*

After removing duplicates, the systematic literature search revealed 4,519 potentially relevant studies. The screening of titles and abstracts excluded 4,289 studies. Seventeen potentially relevant studies were identified through other sources (i.e., reference lists of relevant papers and reviews, hand search of key words via the Internet). The remaining 247 potentially relevant papers were analyzed on the basis of full texts and our pre-defined eligibility criteria. Finally, 13 studies were included in the quantitative analysis. Since the studies of Cyarto et al. (2008a, 2008b) examined the same sample, we considered them as one study in our further

analyses. The same procedure was done with the studies of van Roie et al. (2010) and Opdenacker, Delecluse, and Boen (2011). The provided tables consequently include a total of 11 studies. Three out of the 11 studies conducted a BT (Hinman, 2002; Lindemann, Rupp, Muche, Nikolaus, & Becker, 2004; Wu et al., 2010), two studies conducted a RT (Boshuizen, Stemmerik, Westhoff, & Hopman-Rock, 2005; Watson et al., 2015), and six studies conducted a combined BT/RT (Almeida et al., 2013; Cyarto et al., 2008b, 2008a; Donat & Oezcan, 2007; Karahan et al., 2015; Lacroix et al., 2016; Opdenacker et al., 2011; van Roie et al., 2010). According to the limited number of studies implementing a single BT/RT, we computed overall  $SMD_{bs}$  including all types of training (i.e., BT, RT, and combined BT/RT). Tests assessing static steady-state balance (e.g., time during SLS) were used in six studies (Boshuizen et al., 2005; Cyarto et al., 2008b; Donat & Oezcan, 2007; Lacroix et al., 2016; Lindemann et al., 2004; Wu et al., 2010), five studies assessed proxies of dynamic steady-state balance (e.g., gait speed) (Almeida et al., 2013; Boshuizen et al., 2005; Hinman, 2002; Lacroix et al., 2016; Lindemann et al., 2004), nine studies tested proactive balance (e.g., TUG) (Almeida et al., 2013; Boshuizen et al., 2005; Cyarto et al., 2008b, 2008a; Donat & Oezcan, 2007; Karahan et al., 2015; Lacroix et al., 2016; Lindemann et al., 2004; Watson et al., 2015; Wu et al., 2010), one study tested reactive balance (i.e., sway path after perturbation on a moveable platform) (Lacroix et al., 2016), four studies assessed a balance test battery (i.e., BBS) (Almeida et al., 2013; Donat & Oezcan, 2007; Hinman, 2002; Karahan et al., 2015). Due to the limited number of studies testing reactive balance, we did not calculate  $SMD_{bs}$  for this outcome category. Given a total of five studies assessing lower extremity muscle strength/power (e.g., 5CRT) (Almeida et al., 2013; Cyarto et al., 2008a; Lacroix et al., 2016; Opdenacker et al., 2011; van Roie et al., 2010; Watson et al., 2015), sub-analyses of measures of muscle strength and measures of muscle power, respectively, were not possible. Table 2 displays the characteristics of the 11 included studies with a total of 621 participants (209 male/412 female; because two studies reported sex distribution only for the total sample, we estimated the distribution for these studies). A total of 341 participants received a supervised and 280 participants received an unsupervised exercise program with sample sizes of the groups ranging from 10 to 81 subjects. The mean age of the participants was 73.6 years with group mean ages ranging from 65.3 to 81.1 years. Mean values of body mass ( $70.9 \pm 4.7$  kg), height ( $1.63 \pm 0.04$  m), and body mass index ( $26.6 \pm 2.0$  kg/m<sup>2</sup>) of the identified data ( $n = 389$ ) suggested that conclusions of the current meta-analysis are relevant to the older population.

### Methodological quality of the included trials

The quality of the included studies was moderate, with a median PEDro score of 5 (range 4-8) (Maher et al., 2003). Five out of 11 studies reached the cut-off value for high-quality RCTs of 6 on the PEDro scale (Table 3). Further, only a limited number of studies provided detailed information regarding the conducted training protocols. In particular, the type of individual exercises, number of exercises per training session, and training intensity were reported incompletely.

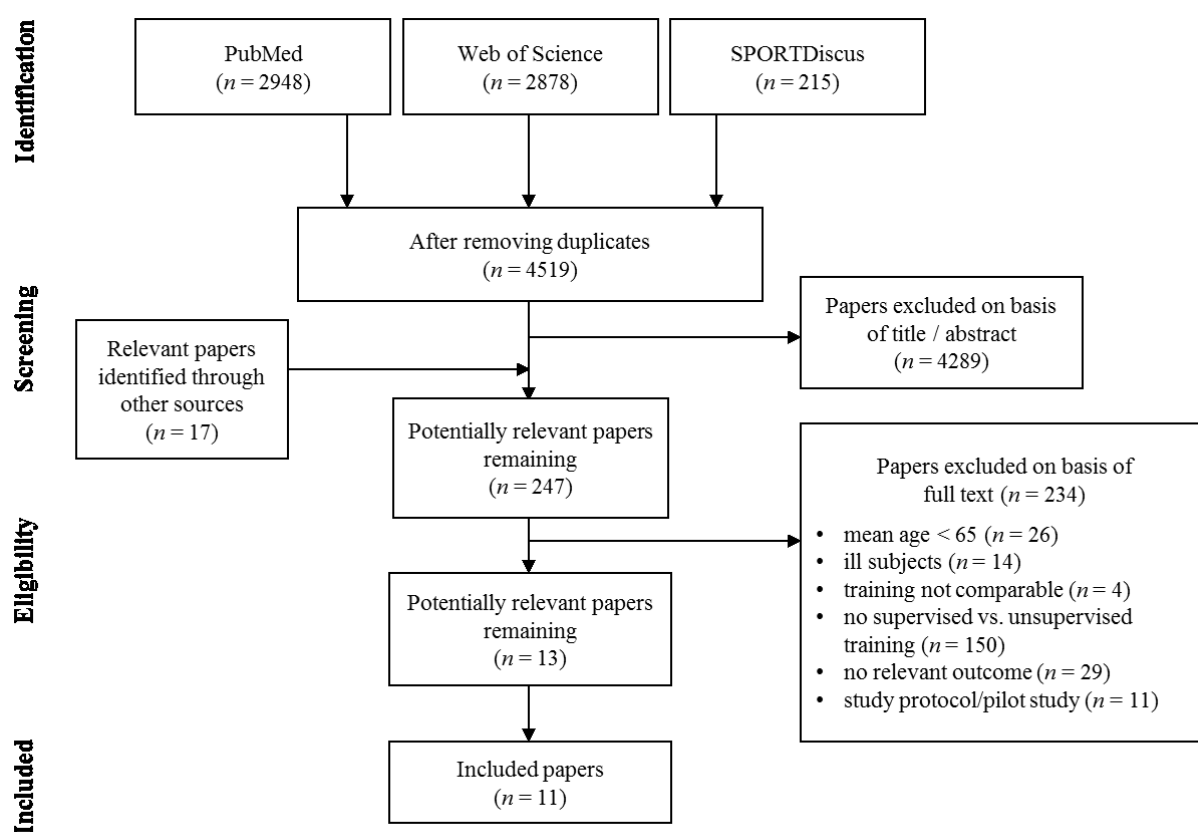


Figure 1: Flowchart illustrating the different phases of the search and study selection.

**Table 2:** Studies examining the effects of supervised vs. unsupervised balance/resistance training on measures of balance and muscle strength/power in older adults.

References	Subjects		Intervention groups		Training modalities		Type of tests	% change (pre-post)	SMD <sub>ws</sub>	SMD <sub>bs</sub> (SUP vs. UNSUP)
	N (M/F)	Age (years)	Period (weeks)	Frequency / Session	Modalities of supervision	Frequency / Session				
Almeida et al. (2013)	50 (8/42)	78.6 ± 4.5	SUP: CRT (lower extremity resistance, static/dynamic balance, stretching exercises) UNSUP: CRT (lower extremity resistance, static/dynamic balance, stretching exercises)	24	3/50	SUP: supervised in all sessions UNSUP: supervised session every other week (12 total)	DB (tandem walk; cm/s)  PB (TUG; s)	SUP: +17.1% (↑) UNSUP: +24.6% (↑) SUP: -27.6% (↑) UNSUP: -22.6% (↑) SUP: 0.42 UNSUP: 0.97	0.26	0.86
		79.2 ± 5.1								
Boshuizen et al. (2005)	32 (2/30)	79.7 ± 6.9	SUP: RT (emphasis on thigh muscle strength exercises) UNSUP: RT (emphasis on thigh muscle strength exercises)	10	3/60	SUP: 2 sessions/ week supervised by physical therapist UNSUP: 1 session/ week supervised by physical therapist	SB (tandem stance; s)	SUP: -23.5% (↓) UNSUP: +12.7% (↑) SUP: -13.4% (↑) UNSUP: -3.6% (↑) SUP: -8.5% (↑) UNSUP: -2.9% (↑)	-1.02	0.15
		80.0 ± 6.7								







Table 2: continued

References	Subjects		Intervention groups	Training modalities		Type of tests	% change (pre-post)	SMD <sub>ws</sub>	SMD <sub>bs</sub> (SUP vs. UNSUP)
	N (M/F)	Age (years)		Period (weeks)	Frequency / Session				
Lindemann et al. (2004)	21 (n/a)	70.0 ± 6.0 SUP: 69.0 ± 6.1 UNSUP: 71.0 ± 5.9	SUP: BT (exercises on an unstable surface with visual feedback) UNSUP: BT (e.g., static / dynamic, weight shifts)	8	2/20	SUP: all sessions individually supervised UNSUP: 2 supervised sessions (first and fourth session; introduction, exercise manual)	SB (20 s narrow stance; area covered [mm <sup>2</sup> ]) DB (maximum gait speed; m/s) PB (FRT; cm)	SUP: 0.07 UNSUP: -0.19 SUP: 0.52 UNSUP: 0.02 SUP: 0.45 UNSUP: -0.11 SUP: 0.27 UNSUP: 0.82	0.43  0.52  0.20  -0.06
Van Roie et al. (2010) / Opendacker et al. (2011)	120 (n/a)	66.4 ± 4.3 SUP: 66.8 ± 4.5 UNSUP: 66.1 ± 4.1	SUP: CRT (balance, strength, flexibility, endurance exercises) UNSUP: CRT (balance, strength, flexibility, endurance exercises)	44	SUP: 3/60-90 UNSUP: 3/n/a	SUP: all sessions supervised UNSUP: 5 sessions supervised; information brochure	MSP (30sCRT; repetitions)	SUP: -4.1 % (†) UNSUP: +16.9 % (‡) SUP: +6.9 % (†) UNSUP: +0.4 % (†) SUP: +6.5 % (†) UNSUP: -1.0 % (‡) SUP: +5.8 % (†) UNSUP: +16.0 % (†)	0.43  0.52  0.20  -0.06
Watson et al. (2015)	28 (0/28)	66.1 ± 4.8 SUP: 65.3 ± 3.9 UNSUP: 66.7 ± 5.4	SUP: RT (deadlift, squat, jumping chin ups/drop landings, overhead press) UNSUP: RT (lunges, calf raises, standing forward raise, shrugs, stretches)	35	2/30	SUP: all sessions supervised UNSUP: all sessions unpervised	PB (TUG; s)	SUP: 0.34 UNSUP: -0.30 SUP: 0.63 UNSUP: -0.11	0.62  1.45

Table 2: continued

References	Subjects		Intervention groups	Training modalities		Type of tests	% change (pre-post)	SMD <sub>ws</sub>	SMD <sub>bs</sub> (SUP vs. UNSUP)
	N (M/F)	Age (years)		Period (weeks)	Frequency / Session				
Wu et al. (2010)	31 (6/25)	75.0 ± 6.6 SUP: 74.1 ± 6.9 UNSUP: 75.9 ± 6.3	SUP: BT (tai chi including turning, weight shifts, leg bending, single leg stance, arm movements; stretching) UNSUP: BT (tai chi including turning, weight shifts, leg bending, single leg stance, arm movements; stretching)	15	3/60	SUP: all sessions supervised UNSUP: all sessions unsupervised; DVD set containing 45 sessions; written documentation	SUP: +23.8 % (↑) UNSUP: +14.4 % (↑) SUP: -2.9 % (↑) UNSUP: +0.4 % (↓)	SUP: 0.40 UNSUP: 0.19 SUP: 0.15 UNSUP: -0.02	0.23

BT = balance training; BTB = balance test batteries; CRT = combined balance and resistance training; DB = dynamic steady-state balance; F = female; Frequency = training sessions per week; FRT = Functional Reach Test; M = male; MSP = muscle strength/power; PB = proactive balance; RB = reactive balance; RT = resistance training; SB = static steady-state balance; session = duration of a single training session (min); SMD<sub>bs</sub> = between-subject standardized mean difference; SMD<sub>ws</sub> = within-subject standardized mean difference; STS = Sit to Stand Test; SUP = supervised training group; TUG = Timed Up and Go Test; UNSUP = unsupervised training group; 30sCRT = 30 seconds Chair Stand Test; 5CRT = 5 Times Chair Rise Test; ↑ = performance improvement; ↓ = performance decline

**Table 3:** Physiotherapy Evidence Database (PEDro) scores of the reviewed studies.

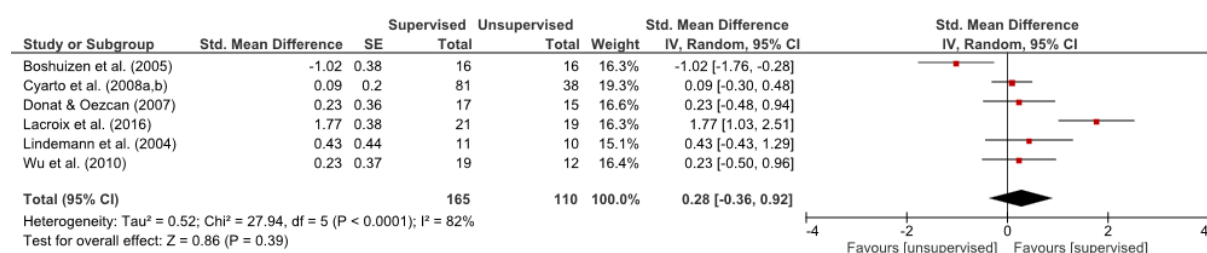
References	Eligibility Criteria	Ran-domiza-tion	Con-cealed allocation	Similar group baselines	Blinding of all subjects	Blinding of all therapists	Blinding of all assessors	Dropout <15%	Intention-to-treat method	Statistical between-group comparisons	Point measures and measures of variability	Score
Almeida et al. (2013)	+	+	-	+	-	-	-	-	-	+	+	4
Boshuizen et al. (2005)	+	+	-	+	-	-	-	-	-	+	+	4
Cyarto et al. (2008a,b)	+	+	+	+	-	-	+	+	+	+	+	8
Donat & Oezcan (2007)	+	+	+	+	-	-	+	-	-	+	+	6
Hinman (2002)	+	+	-	+	-	-	-	+	-	+	+	5
Karahan et al. (2015)	+	+	-	+	-	-	-	+	+	+	+	6
Lacroix et al. (2016)	+	+	-	+	-	-	-	+	-	+	+	5
Lindemann et al. (2004)	+	+	+	+	-	-	+	-	-	+	+	6
Van Roie et al. (2010) / Opendacker et al. (2011)	+	+	+	+	-	-	-	+	-	+	+	6
Watson et al. (2015)	+	+	-	+	-	-	-	-	-	+	+	4
Wu et al. (2010)	+	+	-	+	-	-	-	-	+	+	+	5

+ indicates a "yes" score, - indicates a "no" score; the item "Eligibility Criteria" is not included in the overall score

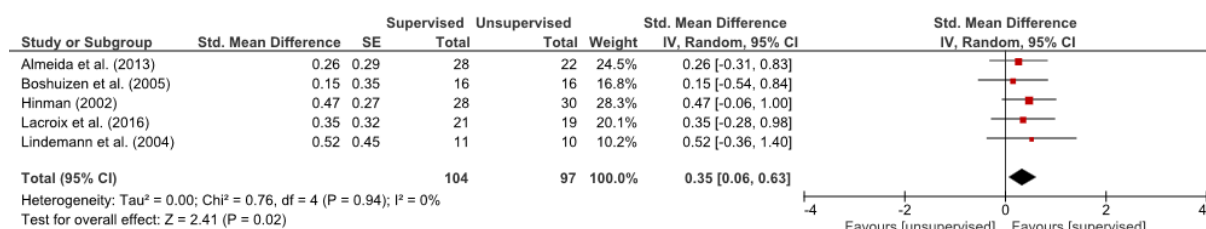
### Effectiveness of supervised versus unsupervised training

Figures 2, 3, 4, 5, 6, and 7 illustrate the effects of supervised versus unsupervised BT and/or RT on proxies of static/dynamic steady-state balance, proactive balance, balance test batteries, overall balance performance, and muscle strength/power.

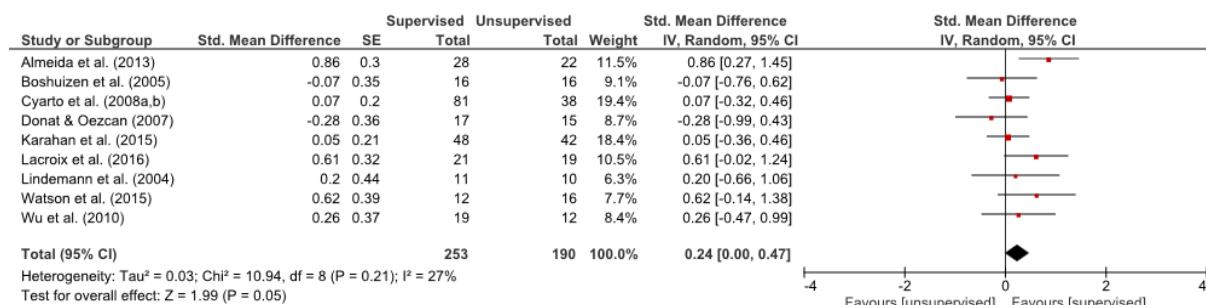
Weighted mean  $SMD_{bs}$  added up to 0.28 for static steady-state balance (six studies; 95 % CI -0.36 to 0.92; overall effect:  $p = 0.39$ ;  $I^2 = 82\%$ ,  $\chi^2 = 27.94$ ,  $df = 5$ ,  $p < 0.0001$ ), 0.35 for variables of dynamic steady-state balance (five studies; 95 % CI 0.06-0.63; overall effect:  $p = 0.02$ ;  $I^2 = 0\%$ ,  $\chi^2 = 0.76$ ,  $df = 4$ ,  $p = 0.94$ ), 0.24 for variables of proactive balance (nine studies; 95 % CI 0.00-0.47; overall effect:  $p = 0.05$ ;  $I^2 = 27\%$ ,  $\chi^2 = 10.94$ ,  $df = 8$ ,  $p = 0.21$ ), 0.53 for balance test batteries (four studies; 95 % CI 0.09-0.98; overall effect:  $p = 0.02$ ;  $I^2 = 62\%$ ,  $\chi^2 = 7.93$ ,  $df = 3$ ,  $p = 0.05$ ), and 0.40 for overall balance performance (ten studies; 95 % CI 0.17-0.63; overall effect:  $p < 0.001$ ;  $I^2 = 33\%$ ,  $\chi^2 = 13.38$ ,  $df = 9$ ,  $p = 0.15$ ), indicating small-to-medium effects in favor of SUP. For variables of muscle strength/power, weighted mean  $SMD_{bs}$  amounted to 0.51 (five studies; 95 % CI 0.03-0.99; overall effect:  $p = 0.04$ ;  $I^2 = 76\%$ ,  $\chi^2 = 16.88$ ,  $df = 4$ ,  $p = 0.002$ ), indicating a medium effect in favor of SUP. To examine the possible influence of study quality on the effects, we compared the PEDro scores of the studies used in the different outcome categories (e.g., static/dynamic steady-state balance) using the Kruskal-Wallis Test. No statistically significant difference was assessed ( $\chi^2 = 1.31$ ,  $df = 5$ ,  $p = 0.934$ ). Overall, 25 out of 30 computed  $SMD_{bs}$  (SUP vs. UNSUP) across studies were positive and showed a favorable effect of SUP ( $0.05 \leq SMD_{bs} \leq 1.77$ ). Within-subject SMD was larger in SUP ( $-0.26 \leq SMD_{ws} \leq 1.86$ ) compared to UNSUP ( $-0.30 \leq SMD_{ws} \leq 1.34$ ) in 23 out of 30 events (Table 2).



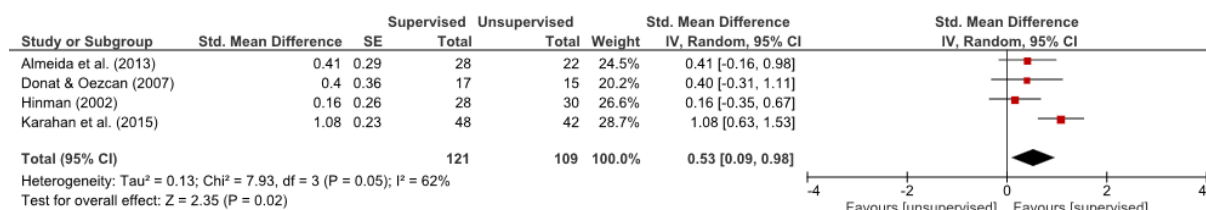
**Figure 2:** Effects of supervised vs. unsupervised balance and/or resistance training on measures of static steady-state balance. *CI* = confidence interval; *df* = degrees of freedom; *IV* = inverse variance; *Random* = random-effects analysis model, *SE* = standard error, *Std.* = standardized



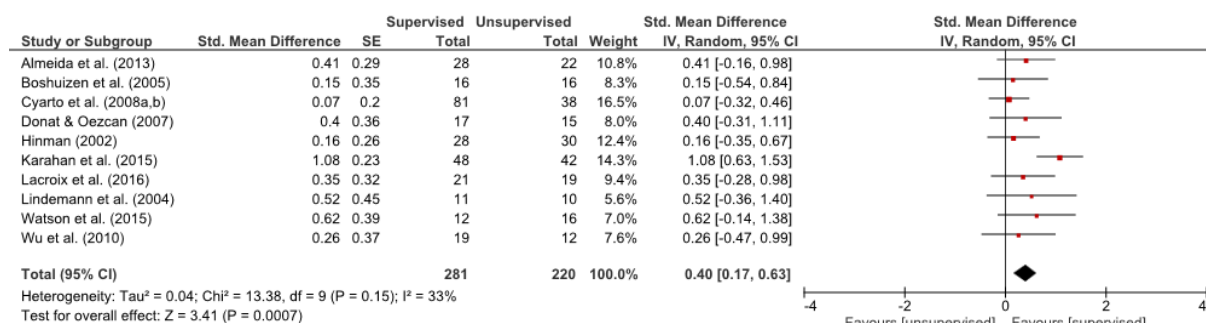
**Figure 3:** Effects of supervised vs. unsupervised balance and/or resistance training on measures of dynamic steady-state balance. *CI* = confidence interval; *df* = degrees of freedom; *IV* = inverse variance; *Random* = random-effects analysis model, *SE* = standard error, *Std.* = standardized



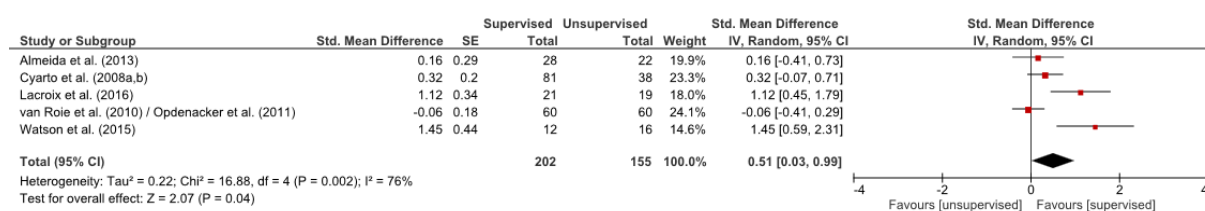
**Figure 4:** Effects of supervised vs. unsupervised balance and/or resistance training on measures of proactive balance. *CI* = confidence interval; *df* = degrees of freedom; *IV* = inverse variance; *Random* = random-effects analysis model, *SE* = standard error, *Std.* = standardized



**Figure 5:** Effects of supervised vs. unsupervised balance and/or resistance training on performance in balance test batteries. *CI* = confidence interval; *df* = degrees of freedom; *IV* = inverse variance; *Random* = random-effects analysis model, *SE* = standard error, *Std.* = standardized



**Figure 6:** Effects of supervised vs. unsupervised balance and/or resistance training on overall balance performance. *CI* = confidence interval; *df* = degrees of freedom; *IV* = inverse variance; *Random* = random-effects analysis model, *SE* = standard error, *Std.* = standardized



**Figure 7:** Effects of supervised vs. unsupervised balance and/or resistance training on measures of muscle strength/power. *CI* = confidence interval; *df* = degrees of freedom; *IV* = inverse variance; *Random* = random-effects analysis model, *SE* = standard error, *Std.* = standardized

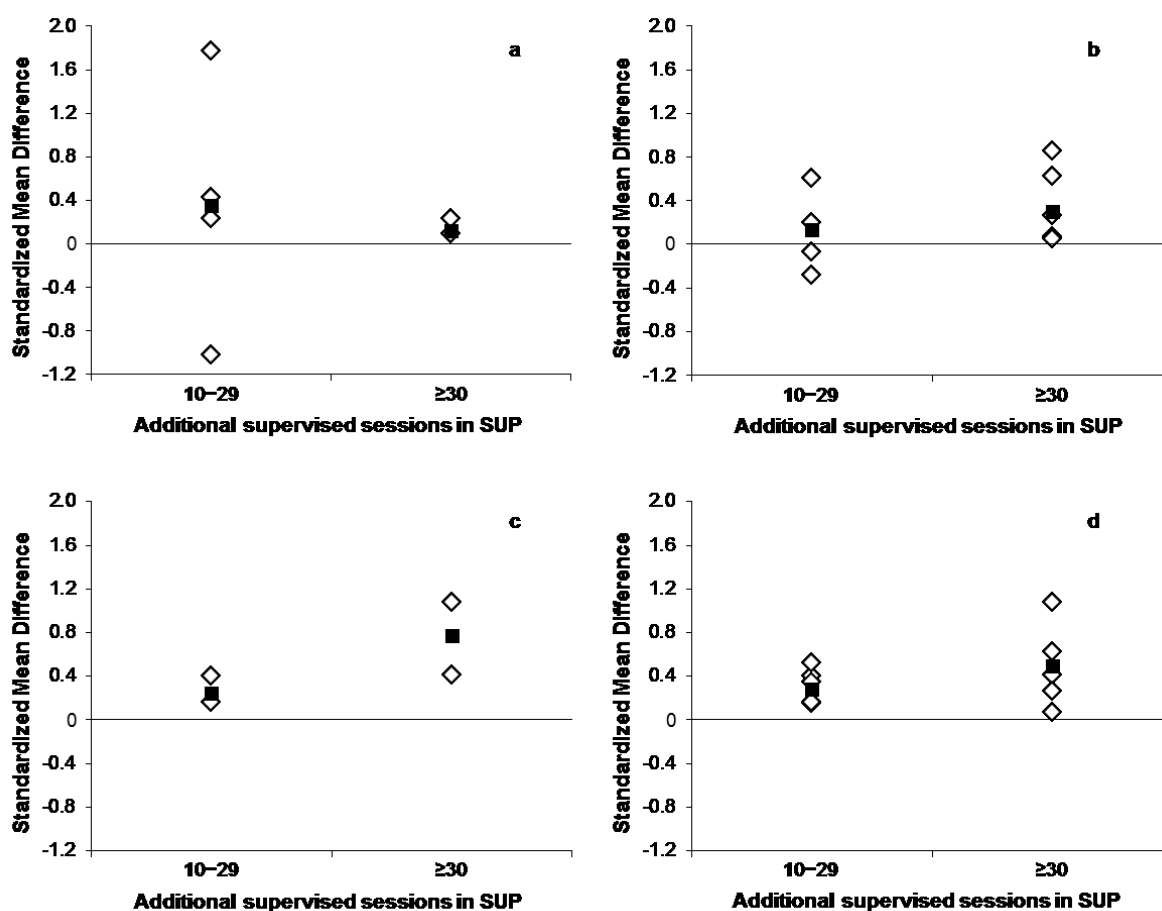
### *Dose-response relationships*

Figure 8 illustrates dose-response relationships for the number of additional supervised sessions in SUP compared with UNSUP (i.e., number of supervised sessions in SUP – number of supervised sessions in UNSUP). Additionally, Figure 9 shows relationships regarding the presence or absence of supervised sessions in UNSUP.

### *Number of additional supervised sessions in supervised training groups*

We calculated weighted mean  $SMD_{bs}$  for studies that implemented up to 29 additional supervised sessions in SUP and compared this value with weighted mean  $SMD_{bs}$  of studies that implemented  $\geq 30$  additional supervised sessions in SUP. An additional number of 10-29 supervised sessions in SUP compared with UNSUP revealed the largest effects for static steady-state balance (10-29: weighted mean  $SMD_{bs}$  = 0.35, four studies, 95 % CI -0.79-1.50;  $\geq 30$ : weighted mean  $SMD_{bs}$  = 0.12, two studies, 95 % CI -0.22-0.47), dynamic steady-state balance (10-29:  $SMD_{bs}$  = 0.37, four studies, 95 % CI 0.05-0.70;  $\geq 30$ :  $SMD_{bs}$  = 0.26, one study, 95 % CI -0.31-0.83), and muscle strength/power (10-29:  $SMD_{bs}$  = 1.12, one study, 95 % CI 0.45-1.79;  $\geq 30$ :  $SMD_{bs}$  = 0.35, four studies, 95 % CI -0.12-0.82). In contrast,  $\geq 30$  additional supervised sessions in SUP produced the largest effects on proactive balance (10-29: weighted mean  $SMD_{bs}$  = 0.13, four studies, 95 % CI -0.27-0.54;  $\geq 30$ : weighted mean  $SMD_{bs}$  = 0.30, five studies, 95 % CI -0.01-0.62), balance test batteries (10-29:  $SMD_{bs}$  = 0.24, two studies, 95 % CI -0.17-0.66;  $\geq 30$ :  $SMD_{bs}$  = 0.77, two studies, 95 % CI 0.11-1.42), and overall balance performance (10-29:  $SMD_{bs}$  = 0.28, five studies, 95 % CI -0.01-0.57;  $\geq 30$ :  $SMD_{bs}$  = 0.49, five studies, 95 % CI 0.07-0.91) (Figure 8). Study quality as measured with the PEDro scale did not significantly differ between the two groups (Mann-Whitney *U* Test:  $U = 14.00$ ,  $p = 0.849$ ).





**Figure 8:** Dose-response relationships for additional supervised sessions in supervised training groups (SUP) compared with unsupervised training groups (UNSUP) on measures of (a) static steady-state balance, (b) proactive balance, (c) balance test batteries, and (d) overall balance performance. Each rimmed diamond illustrates between-subject standardized mean difference (SMD<sub>bs</sub>) per single study (SUP vs. UNSUP). Filled black squares represent weighted mean SMD<sub>bs</sub> of all studies.

#### *Presence or absence of supervised sessions in unsupervised training groups*

We calculated weighted mean SMD<sub>bs</sub> for studies that did not implement supervised sessions in UNSUP and compared this value with weighted mean SMD<sub>bs</sub> of studies that implemented supervised sessions in UNSUP. Our analyses revealed that studies with no supervised sessions in UNSUP produced the largest effects in favor of SUP on measures of static steady-state balance (no supervised sessions in UNSUP: weighted mean SMD<sub>bs</sub> = 1.00, two studies, 95 % CI -0.51-2.51; supervised sessions in UNSUP: weighted mean SMD<sub>bs</sub> = -0.06; four studies, 95 % CI -0.62-0.49), measures of dynamic steady-state balance (no supervised sessions in UNSUP: SMD<sub>bs</sub> = 0.42, two studies, 95 % CI 0.02-0.82; supervised sessions in UNSUP: SMD<sub>bs</sub> = 0.28; three studies, 95 % CI -0.12-0.67), measures of proactive balance (no supervised sessions in UNSUP: SMD<sub>bs</sub> = 0.28, four studies, 95 % CI -0.01-0.57; supervised sessions in UNSUP: SMD<sub>bs</sub> = 0.17; five studies, 95 % CI -0.21-0.55), balance test batteries

(no supervised sessions in UNSUP:  $SMD_{bs} = 0.63$ , two studies, 95 % CI  $-0.27-1.53$ ; supervised sessions in UNSUP:  $SMD_{bs} = 0.41$ ; two studies, 95 % CI  $-0.04-0.85$ ), and overall balance performance (no supervised sessions in UNSUP:  $SMD_{bs} = 0.52$ , five studies, 95 % CI  $0.13-0.91$ ; supervised sessions in UNSUP:  $SMD_{bs} = 0.23$ ; five studies, 95 % CI  $-0.02-0.49$ ) as well as measures of muscle strength/power (no supervised sessions in UNSUP:  $SMD_{bs} = 1.24$ , two studies, 95 % CI  $0.72-1.77$ ; supervised sessions in UNSUP:  $SMD_{bs} = 0.12$ ; three studies, 95 % CI  $-0.12-0.36$ ) (Figure 9). Study quality as measured with the PEDro scale did not significantly differ between the two groups (Mann-Whitney  $U$  Test:  $U = 10.50$ ,  $p = 0.391$ ).

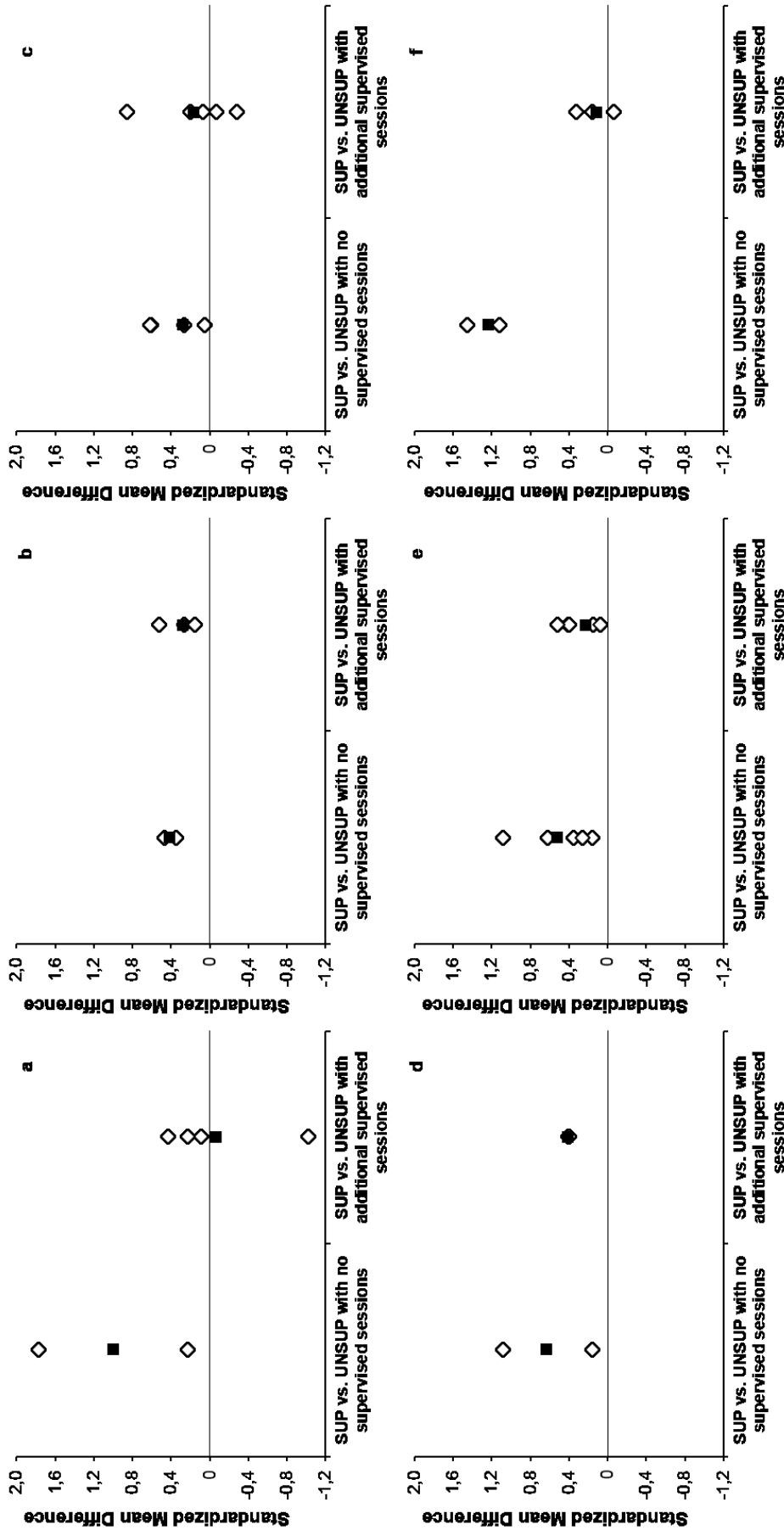


Figure 9: Comparison of the effects of studies with and without supervised sessions in the unsupervised training groups (UNSUP) on measures of (a) static steady-state balance, (b) dynamic steady-state balance, (c) proactive balance, (d) balance test batteries, (e) overall balance performance, and (f) muscle strength/power. Each *rimmed diamond* illustrates between-subject standardized mean difference (SMD<sub>bs</sub>) per single study (SUP vs. UNSUP). *Filled black squares* represent weighted mean SMD<sub>bs</sub> of all studies.

## Discussion

This is the first systematic review and meta-analysis that examined the effects of supervised versus unsupervised BT and/or RT on measures of balance and muscle strength/power in older adults. The main finding of our analyses supported the hypothesis that supervised compared with unsupervised exercise programs showed larger effects in promoting measures of balance and muscle strength/power ( $0.24 \leq \text{SMD}_{\text{bs}} \leq 0.53$ ). However, the effects in favor of SUP were dampened when SUP was compared with a specific form of UNSUP including small doses of supervised sessions. These results could complement existing recommendations for BT and RT in older adults based on meta-analytic approaches (Borde, Hortobágyi, & Granacher, 2015; Lesinski et al., 2015; Nicola & Catherine, 2011; Steib, Schoene, & Pfeifer, 2010). We discuss our findings by interpreting the effects based on the already published literature.

### *Effects of supervised versus unsupervised training on measures of balance and muscle strength/power*

The analyses of  $\text{SMD}_{\text{bs}}$  are based on data from 621 participants aged 73.6 years (range 65-81 years). The number of participants in the respective outcome categories varied from 201 to 501. To provide an overall characterization of participants' mobility, dynamic steady-state balance measured by average gait speed (habitual and maximal speeds combined) was 1.21 m/s ( $n = 151$ ) at the baseline of the interventions. This speed is in line with another meta-analysis, reporting on the effects of three types of exercise interventions on gait speed (Hortobágyi et al., 2015). Thus, our data are relevant to healthy mobile older adults. Because the included studies did not report exercise intensity, it was not possible to determine how intensity affects the efficacy of either form of intervention. However, supervised and unsupervised interventions were comparable in terms of the implemented exercises, training periods, training frequencies, and single session durations (Table 2).

The data confirm our hypothesis that supervised versus unsupervised training interventions improve proxies of balance and muscle strength/power to a greater extent. The examined effect sizes for static/dynamic steady-state balance (0.28/0.35), proactive balance (0.24), and overall balance performance (0.40) were small compared with medium effects for balance test batteries (0.53) and measures of muscle strength/power (0.51). While there are no review data available on such comparisons in healthy older adults, our results agree with a meta-analysis that compared the effects of supervised versus unsupervised exercise therapy in patients with

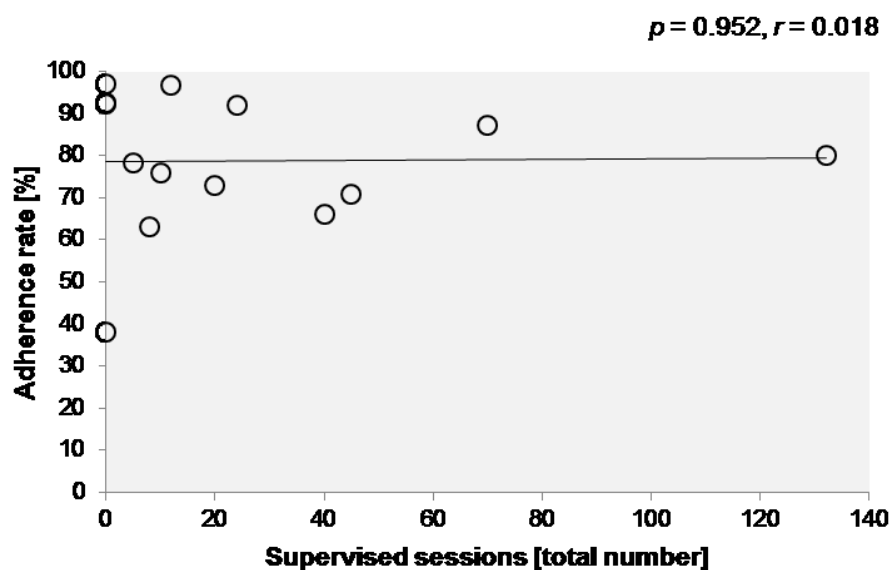
intermittent claudication (Fokkenrood et al., 2013). Supervised compared to unsupervised exercise therapy showed statistically significant benefits on treadmill walking distance (maximal and pain-free) [effect sizes (SMD): 0.48-0.70]. The greater gait speed effects might be related to the claudication cohort being ~8 years younger (mean age 65.8 years) than the cohorts we examined and to a greater effectiveness of exercise feedback to increase their slow gait at baseline. Ashworth et al. (2005) also confirmed the hypothesis that supervised compared with unsupervised exercise therapy is more effective at improving distance walked and time to claudication pain in patients with peripheral vascular disease, but the effects remained unclear in patients with chronic obstructive pulmonary disorder. In contrast, a recently published meta-analysis (Taylor et al., 2015) reported that home- and center-based forms of cardiac rehabilitation seem to be equally effective to improve clinical and health-related quality of life outcomes (e.g., exercise capacity, blood lipids, blood pressure) in low risk patients after myocardial infarction/revascularization, or with heart failure. Other reviews and meta-analyses investigated the effects of either facility-based and/or home-based exercise programs compared to control groups. For example, Thiebaud, Funk, and Abe (2014) stated in their systematic review that the effects of home-based resistance training (partly supervised) were small compared with traditional (e.g., facility-based) resistance training programs, although home-based interventions seem to have the potential to increase strength in older adults. This is in line with our findings of within-subject SMDs, which are larger in the supervised training groups. In this context, Gillespie et al. (2012) reported effects of various interventions (e.g., group exercise, individual home-based exercise, vitamin D supplementation) compared with controls on the risk of falling and rate of falls. Multicomponent (two or more categories of exercise) supervised group exercise achieved a statistically significant reduction in the risk of falling [pooled risk ratio (RR) = 0.85] and rate of falls [pooled rate ratio (RaR) = 0.71], as did multi-component individual home-based exercise (RR = 0.78; RaR = 0.68). However, most of the individually home-based interventions comprised additional supervised sessions by exercise instructors, which complicates the distinction between group- and home-based interventions. Because falls were not documented in most of the included studies of the present review, a direct comparison with the results of Gillespie et al. (2012) is not possible. Future studies should clearly report the location of exercise interventions (e.g., center-, group-, gym-, home-based) and the form of supervision (e.g., supervised, unsupervised, combinations).

How does supervision increase exercise intervention outcomes? Greater adaptations to supervised versus unsupervised exercise programs may be attributed to the participants executing the exercises with a better quality, resulting in a higher training intensity (Lacroix et al., 2016), a better adherence and thus a higher training volume (Stathi, McKenna, & Fox, 2010; Wu et al., 2010), or a beneficial influence on cognitive determinants (e.g., executive function) of physical ability (Forte, Boreham et al., 2013; Forte, Pesce et al., 2013).

A higher quality in the execution of exercises could mean that participants receiving versus those not receiving supervision execute the exercises more precisely (i.e., without additional movements), with a larger range of motion, more forcefully, with shorter pauses, or in other ways that increase exercise intensity. However, none of the included studies reported exercise intensity. Lacroix et al. (2016) described that participants of SUP and UNSUP achieved similar mean stages of progression, which implied a higher perceived exertion and thus larger adaptations in SUP vs. UNSUP. Previous meta-analyses (Borde et al., 2015; Nicola & Catherine, 2011; Steib et al., 2010) on dose-response relationships of RT in older adults confirmed that high training intensities (~70-80 % one-repetition maximum) produced larger effects on measures of muscle strength. Comparable recommendations for BT intensities are still lacking.

Higher adherence rates in SUP vs. UNSUP could also result in greater exercise adaptations owing to an increase in training volume. However, rates of adherence to exercise interventions are heterogeneous in older adults (Kohler, Kressig, Schindler, & Granacher, 2012). For example, Stathi et al. (2010) found that the adherence rate to a 12-month supervised program (93 %) was higher compared with an unsupervised program (85 %). On the other hand, Ashworth and colleagues (2005) stated that adherence to exercises seemed to be better in home-based compared with center-based physical activity programs for adults > 50 years with cardiovascular risk factors. We found no significant difference ( $p = 0.658$ ) between SUP ( $80.9 \pm 11.5$  %) and UNSUP ( $76.8 \pm 20.8$  %) adherence rates in the 11 studies. Because six of 11 UNSUP included some supervision, the absolute adherence rates may be biased and overestimated. A lack of an association between adherence rates and the total number of supervised sessions may imply that those who attended exercise classes would have done so without supervision ( $p = 0.952$ ,  $r = 0.018$ ) (Figure 10). In more general terms, we interpret the data to mean that probably there is a segment of people who exercise regardless of supervision and those who do not wish to exercise will do so regardless of the availability of supervision. An

overestimation of adherence in UNSUP through diary data could also contribute to the low correlation.



**Figure 10:** Association between the adherence rate to training and the total number of supervised sessions within groups. There are 14 data points in the graph because seven of the included studies reported adherence rates for both supervised and unsupervised groups. The association is characterized by  $y = 0.0078x + 78.61$  and  $r^2 = 0.0003$ .

Cognitive function may also contribute to the larger responses to exercise training in SUP vs UNSUP. There is evidence that executive function acts as a mediator in older adults' improved mobility after an exercise intervention, substantiated by the low correlation between changes in gait speed and leg muscle power (Beijersbergen, Granacher, Vandervoort, DeVita, & Hortobágyi, 2013). Recent research points to a mechanism that acts through cognitive flexibility to increase older adults' maximal gait speed as a result of an increase in lower extremity muscle power (Forte, Pesce et al., 2013). This mechanism could operate specific to the type of intervention because different types of training (i.e., multi-component; resistance) might promote executive function through different pathways (i.e., directly through inhibitory capacity; indirectly through enhanced muscle strength) (Forte, Boreham et al., 2013).

It is conceivable that supervision favorably affects executive function. Because a combination of physical and cognitive training seems to maximize cognitive benefits (Oswald, Gunzelmann, Rupprecht, & Hagen, 2006), it is possible that supervision affords cognitive challenges, a stimulus that is absent when someone exercises unsupervised. The cognitive stimulus could include but is not limited to planning and decisions associated with transportation, scheduling, social interaction, adherence to appointments, and peer pressure. As adherence and supervision seem to be unrelated, future studies should include tests of cognitive function and clearly

state levels of perceived exercise intensity, to highlight possible reasons for the greater effectiveness of exercising with than without supervision.

Even though we can only speculate about the superiority of SUP, the improvements and the differences in improvements between SUP and UNSUP are functionally relevant. Measures of static steady-state balance ( $SMD_{bs} = 0.28$ ) improved on average by 48.7 % in SUP and 16.5 % in UNSUP. This corresponds to a larger improvement in SUP of 32.2 %. Further, analyses revealed a net gain of 4.3 % for measures of proactive balance ( $SMD_{bs} = 0.24$ ; SUP: 10.1 %, UNSUP: 5.8 %), 1.2 % for the BBS ( $SMD_{bs} = 0.53$ ; SUP: 3.0 %, UNSUP: 1.8 %), and 2.1 % for measures of muscle strength/power ( $SMD_{bs} = 0.51$ ; SUP: 15.8 %, UNSUP: 13.7 %) in SUP compared with UNSUP. For measures of dynamic steady-state balance (including habitual and fast walking tests as well as one tandem walking test), SUP increased speed from 1.11 m/s to 1.19 m/s by 0.08 m/s. UNSUP also increased speed from 1.09 m/s to 1.12 m/s, resulting in a larger improvement of 0.05 m/s for SUP (4.5 %;  $SMD_{bs} = 0.35$ ). Exclusion of the tandem walk test used in one study makes this result even clearer (net gain of SUP: 0.07 m/s). Meaningful changes of gait speed have been reported in the literature and ranged from 0.04 m/s (small) to 0.14 m/s (substantial) (Hortobágyi et al., 2015; Perera, Mody, Woodman, & Studenski, 2006). Because the present meta-analysis focused on healthy older adults, a gain of 0.08 m/s in SUP alone and a net gain of 0.05-0.07 compared to UNSUP can be seen as a clinically meaningful benefit.

Diversity of measures of static steady-state balance and muscle strength/power resulted in high  $I^2$  values of 82 % and 76 %, respectively. For example, three studies assessed leg power by time (e.g., 5CRT), while two studies tested leg power by frequency (number of chair stands in 30 s). However, the largest effects in favor of SUP were found for balance test batteries (i.e., BBS) and measures of muscle strength/power. Since the BBS contains tasks like chair rises, comparable effects could have occurred because of the functional overlap of these tests. A possible explanation of enhanced performances in UNSUP may be that some studies implemented supervised sessions in these groups. Our hypothesis is supported by the larger effects in favor of SUP when compared to UNSUP with no additional supervised sessions, as discussed below.

#### *Dose-response relations of supervision during training*

Increasing the number of supervised sessions in SUP revealed an inconsistent dose-response relationship. Some measures (i.e., static/dynamic steady-state balance, muscle strength/power)



revealed larger effects for an additional number of 10-29 additional sessions compared with  $\geq 30$  additional supervised sessions in SUP vs. UNSUP. Others (proactive balance, balance test batteries, overall balance performance) revealed larger effects for an additional number of  $\geq 30$  additional supervised sessions in SUP. Differences of effects (10-29 versus  $\geq 30$  additional supervised sessions in SUP) were small except for measures of muscle strength/power. The data suggest a threshold of supervision beyond which an additional number of supervised sessions has no effects. This observation is affected by the low number of studies, especially for measures of dynamic steady-state balance and muscle strength/power. For these variables, only one study was available for the first category (i.e., 10-29 additional supervised sessions in SUP).

The comparison of studies that implemented a strictly unsupervised UNSUP with studies that implemented supervised sessions in UNSUP revealed a more consistent result. We found that all measures showed larger effects in favor of SUP for studies with no supervised session in UNSUP. This implies a distinct superiority of SUP versus strictly unsupervised training ( $0.28 \leq \text{SMD}_{\text{bs}} \leq 1.24$ ), whereas this superiority seems to fade when compared to UNSUP with additional (though small number of) supervised sessions ( $-0.06 \leq \text{SMD}_{\text{bs}} \leq 0.41$ ). This difference particularly became apparent for measures of static steady-state balance and muscle strength/power. It seems that supervision is most likely essential in exercises that require a technically correct execution (i.e., static steady-state balance and muscle strength/power). Possibly, a small number of supervised sessions (mean number of supervised sessions in UNSUP with supervised sessions: 6.7) is sufficient to enhance performance compared to completely unsupervised programs, but not to the extent as fully supervised programs do. An essential point could be the lack of extensive learning of the exercises in the completely unsupervised groups, leading to ineffective exercise execution. Given the lack of reporting training intensity in the included studies, we were not able to examine how exercise intensity might have affected training outcomes.

### *Limitations of study*

One limitation is the inclusion of a low number of studies, making the conclusions preliminary. A second limitation is the lack of a consistent set of balance and muscle strength tests, which would be useful to conduct more comprehensive meta-analyses in the future. A third limitation is the lack of a clear terminology of supervised or unsupervised exercises interventions. Indeed, some of the studies used supervised sessions for their UNSUP, which may have

led to distorted results. Further, our dose-response analysis is limited because we indirectly compared  $SMD_{bs}$  across studies and not in a single controlled study. The median PEDro score of 5 suggested a moderate study quality. All studies reported adequate randomization. However, nine of the 11 included studies used no blinding of the assessors and seven of the 11 included studies did not conceal the allocation. As studies without adequate allocation concealment tend to exaggerate treatment effects compared with those with adequate concealment, the effects favoring supervised regimens may have been overestimated (Liberati et al., 2009; Pildal et al., 2007). Most of the funnel plots were symmetrical, minimizing the effects of bias in the conclusions. However, an overestimation of the effects by SUP vs. UNSUP on the outcomes cannot be excluded owing to the low number of studies. Finally, an important limitation is that our analyses are relevant to reductions in fall risks but not directly to reductions in the number of falls.

## Conclusions

This systematic review and meta-analysis demonstrated that supervised exercise programs are superior compared to unsupervised exercise programs in improving measures of balance and muscle strength/power in older adults. Based on data from 11 studies, small-to-medium effects were detected in favor of supervised regimens for all examined measures of balance and muscle strength/power. Effects in favor of supervised exercise programs were larger when compared to fully unsupervised exercise programs instead of unsupervised programs with a small number of supervised sessions. Consequently, supervised sessions (i.e., two out of three sessions per week) should be included in BT and/or RT programs by practitioners and therapists to ensure optimal and clinically relevant effects. If circumstances (e.g., resources, mobility problems, transportation, motivation to go outside the house, financial problems) do not allow supervised exercises, completely or partly unsupervised exercise programs could still be an option to improve balance and strength performance. Future high-quality RCTs should evaluate graded approaches, implementing different stages of exercise supervision (i.e., all sessions supervised vs. lower number of sessions supervised vs. no supervised sessions) and include measures of cognitive function and exercise intensity to get a clear view of the role of supervision and possible reasons.

## References

- Aagaard, P., Suetta, C., Caserotti, P., Magnusson, S. P., & Kjaer, M. (2010). Role of the nervous system in sarcopenia and muscle atrophy with aging: strength training as a countermeasure. *Scandinavian journal of medicine & science in sports*, *20*(1), 49–64. <https://doi.org/10.1111/j.1600-0838.2009.01084.x>
- Abrahamova, D., & Hlavacka, F. (2008). Age-related changes of human balance during quiet stance. *Physiological Research*, *57*(6), 957–964.
- Almeida, T. L., Alexander, N. B., Nyquist, L. V., Montagnini, M. L., Santos, A. C., Rodrigues, G. H., . . . Wajngarten, M. (2013). Minimally supervised multimodal exercise to reduce falls risk in economically and educationally disadvantaged older adults. *Journal of Aging and Physical Activity*, *21*(3), 241–259.
- Ashworth, N. L., Chad, K. E., Harrison, E. L., Reeder, B. A., & Marshall, S. C. (2005). Home versus center based physical activity programs in older adults. *The Cochrane Database of Systematic Reviews*, Cd004017. <https://doi.org/10.1002/14651858.CD004017.pub2>
- Beijersbergen, C. M., Granacher, U., Vandervoort, A. A., DeVita, P., & Hortobágyi, T. (2013). The biomechanical mechanism of how strength and power training improves walking speed in old adults remains unknown. *Ageing Research Reviews*, *12*(2), 618–627. <https://doi.org/10.1016/j.arr.2013.03.001>
- Bohannon, R. W. (2006). Reference values for the timed up and go test: a descriptive meta-analysis. *Journal of Geriatric Physical Therapy*, *29*(2), 64–68.
- Bohannon, R. W., & Williams Andrews, A. (2011). Normal walking speed: a descriptive meta-analysis. *Physiotherapy*, *97*(3), 182–189. <https://doi.org/10.1016/j.physio.2010.12.004>
- Borde, R., Hortobágyi, T., & Granacher, U. (2015). Dose-Response Relationships of Resistance Training in Healthy Old Adults: A Systematic Review and Meta-Analysis. *Sports medicine (Auckland, N.Z.)*, *45*(12), 1693–1720. doi: 10.1007/s40279-015-0385-9
- Boshuizen, H. C., Stemmerik, L., Westhoff, M. H., & Hopman-Rock, M. (2005). The effects of physical therapists' guidance on improvement in a strength-training program for the frail elderly. *Journal of Aging and Physical Activity*, *13*(1), 5–22.
- Burns, P. B., Rohrich, R. J., & Chung, K. C. (2011). The levels of evidence and their role in evidence-based medicine. *Plastic and Reconstructive Surgery*, *128*(1), 305.
- Campbell, A. J., & Robertson, M. C. (2007). Rethinking individual and community fall prevention strategies: a meta-regression comparing single and multifactorial interventions. *Age and Ageing*, *36*(6), 656–662. <https://doi.org/10.1093/ageing/afm122>
- Christie, J. (2011). Progressive resistance strength training for improving physical function in older adults. *International Journal of Older People Nursing*, *6*(3), 244–246. <https://doi.org/10.1111/j.1748-3743.2011.00291.x>
- Cohen, J. (1992). A power primer. *Psychological bulletin*, *112*(1), 155–159.
- Cohen-Mansfield, J., Marx, M. S., & Guralnik, J. M. (2003). Motivators and barriers to exercise in an older community-dwelling population. *Journal of Aging and Physical Activity*, *11*(2), 242–253. <https://doi.org/10.1123/japa.11.2.242>
- Cyarto, E. V., Brown, W. J., Marshall, A. L., & Trost, S. G. (2008a). Comparison of the effects of a home-based and group-based resistance training program on functional ability in older adults. *American Journal of Health Promotion*, *23*(1), 13–17. <https://doi.org/10.4278/ajhp.07030120>

- Cyarto, E. V., Brown, W. J., Marshall, A. L., & Trost, S. G. (2008b). Comparative effects of home- and group-based exercise on balance confidence and balance ability in older adults: cluster randomized trial. *Gerontology*, *54*(5), 272–280. <https://doi.org/10.1159/000155653>
- Deeks, J. J., & Higgins, J. P. (2010). *Statistical algorithms in review manager 5 [on behalf of the Statistical Methods Group of The Cochrane Collaboration]*. Retrieved from <http://tech.cochrane.org/revman/documentation/Statistical-methods-in-RevMan-5.pdf>. Accessed 11 Nov 2016
- Donat, H., & Oezcan, A. (2007). Comparison of the effectiveness of two programmes on older adults at risk of falling: unsupervised home exercise and supervised group exercise. *Clinical Rehabilitation*, *21*(3), 273–283. <https://doi.org/10.1177/0269215506069486>
- Fokkenrood, H. J. P., Bendermacher, B. L. W., Lauret, G. J., Willigendael, E. M., Prins, M. H., & Teijink, J. A. W. (2013). Supervised exercise therapy versus non-supervised exercise therapy for intermittent claudication. *The Cochrane Database of Systematic Reviews*, CD005263. doi: 10.1002/14651858.CD005263.pub3
- Forte, R., Boreham, C. A., Leite, J. C., Vito, G. de, Brennan, L., Gibney, E. R., & Pesce, C. (2013). Enhancing cognitive functioning in the elderly: multicomponent vs resistance training. *Clinical Interventions in Aging*, *8*, 19–27. <https://doi.org/10.2147/cia.s36514>
- Forte, R., Pesce, C., Leite, J. C., Vito, G. de, Gibney, E. R., Tomporowski, P. D., & Boreham, C. A. (2013). Executive function moderates the role of muscular fitness in determining functional mobility in older adults. *Aging Clinical and Experimental Research*, *25*(3), 291–298. <https://doi.org/10.1007/s40520-013-0044-7>
- Franco, M. R., Howard, K., Sherrington, C., Ferreira, P. H., Rose, J., Gomes, J. L., & Ferreira, M. L. (2015). Eliciting older people's preferences for exercise programs: a best-worst scaling choice experiment. *Journal of Physiotherapy*, *61*(1), 34–41. <https://doi.org/10.1016/j.jphys.2014.11.001>
- Freiberger, E., Blank, W. A., Salb, J., Geilhof, B., Hentschke, C., Landendoerfer, P., . . . Siegrist, M. (2013). Effects of a complex intervention on fall risk in the general practitioner setting: a cluster randomized controlled trial. *Clinical Interventions in Aging*, *8*, 1079–1088. <https://doi.org/10.2147/cia.s46218>
- Gill, T. M., Allore, H. G., Holford, T. R., & Guo, Z. (2004). Hospitalization, restricted activity, and the development of disability among older persons. *Journal of the American Medical Association*, *292*(17), 2115–2124. <https://doi.org/10.1001/jama.292.17.2115>
- Gillespie, L. D., Robertson, M. C., Gillespie, W. J., Sherrington, C., Gates, S., Clemson, L. M., & Lamb, S. E. (2012). Interventions for preventing falls in older people living in the community. *The Cochrane Database of Systematic Reviews*, *9*, Cd007146. doi: 10.1002/14651858.CD007146.pub3
- Granacher, U., Gruber, M., & Gollhofer, A. (2010). Force production capacity and functional reflex activity in young and elderly men. *Aging Clinical and Experimental Research*, *22*(5-6), 374–382. <https://doi.org/10.3275/6706>
- Granacher, U., Muehlbauer, T., Bridenbaugh, S., Wehrle, A., & Kressig, R. W. (2010). [Age-related differences during single and multi-task walking]. *Deutsche Zeitschrift für Sportmedizin*, *61*(11), 258–263.
- Granacher, U., Muehlbauer, T., Gschwind, Y. J., Pfenninger, B., & Kressig, R. W. (2014). [Assessment and training of strength and balance for fall prevention in the elderly: recommendations of an interdisciplinary expert panel]. *Zeitschrift für Gerontologie und Geriatrie*, *47*(6), 513–526. <https://doi.org/10.1007/s00391-013-0509-5>

- Granacher, U., Muehlbauer, T., Zahner, L., Gollhofer, A., & Kressig, R. W. (2011). Comparison of traditional and recent approaches in the promotion of balance and strength in older adults. *Sports Medicine*, *41*(5), 377–400. <https://doi.org/10.2165/11539920-000000000-00000>
- Hedges, L. V., & Olkin, I. (1985). *Statistical methods for meta-analysis*. San Diego: Academic Press.
- Higgins, J. P., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses. *BMJ*, *327*(7414), 557–560. <https://doi.org/10.1136/bmj.327.7414.557>
- Hill, K. D., Hunter, S. W., Batchelor, F. A., Cavalheri, V., & Burton, E. (2015). Individualized home-based exercise programs for older people to reduce falls and improve physical performance: A systematic review and meta-analysis. *Maturitas*, *82*(1), 72–84. <https://doi.org/10.1016/j.maturitas.2015.04.005>
- Hinman, M. (2002). Comparison of Two Short-term Balance Training Programs for Community-dwelling Older Adults. *Journal of Geriatric Physical Therapy*, *25*(3), 10–20.
- Hortobágyi, T., Lesinski, M., Gäbler, M., VanSwearingen, J., Malatesta, D., & Granacher, U. (2015). Effects of Three Types of Exercise Interventions on Healthy Old Adults' Gait Speed: A Systematic Review and Meta-Analysis. *Sports Medicine*, *45*(12), 1627–1643.
- Howe, T. E., Rochester, L., Jackson, A., Banks, P. M., & Blair, V. A. (2007). Exercise for improving balance in older people. *The Cochrane Database of Systematic Reviews*, Cd004963. <https://doi.org/10.1002/14651858.CD004963.pub2>
- Karahan, A. Y., Tok, F., Taskin, H., Kucuksarac, S., Basaran, A., & Yildirim, P. (2015). Effects of Exergames on Balance, Functional Mobility, and Quality of Life of Geriatrics Versus Home Exercise Programme: Randomized Controlled Study. *Central European Journal of Public Health*, *23 Suppl*, S14-8. <https://doi.org/10.21101/cejph.a4081>
- Kohler, A., Kressig, R. W., Schindler, C., & Granacher, U. (2012). [Adherence rate in intervention programs for the promotion of physical activity in older adults: a systematic literature review]. *Praxis (Bern 1994)*, *101*(24), 1535–1547. <https://doi.org/10.1024/1661-8157/a001129>
- Lacroix, A., Kressig, R. W., Muehlbauer, T., Gschwind, Y. J., Pfenninger, B., Bruegger, O., & Granacher, U. (2016). Effects of a Supervised versus an Unsupervised Combined Balance and Strength Training Program on Balance and Muscle Power in Healthy Older Adults: A Randomized Controlled Trial. *Gerontology*, *62*(3), 275–288. <https://doi.org/10.1159/000442087>
- Lesinski, M., Hortobágyi, T., Muehlbauer, T., Gollhofer, A., & Granacher, U. (2015). Effects of Balance Training on Balance Performance in Healthy Older Adults: A Systematic Review and Meta-analysis. *Sports Medicine*, *45*(12), 1721–1738.
- Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gotzsche, P. C., Ioannidis, J. P., . . . Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *BMJ*, *339*, b2700. <https://doi.org/10.1136/bmj.b2700>
- Lindemann, U., Rupp, K., Mucbe, R., Nikolaus, T., & Becker, C. (2004). Improving balance by improving motor skills. *Zeitschrift für Gerontologie und Geriatrie*, *37*(1), 20–26. <https://doi.org/10.1007/s00391-004-0206-5>
- Lusardi, M. M., Pellecchia, G. L., & Schulman, M. (2003). Functional Performance in Community Living Older Adults. *Journal of Geriatric Physical Therapy*, *26*(3), 14–22.
- Maher, C. G., Sherrington, C., Herbert, R. D., Moseley, A. M., & Elkins, M. (2003). Reliability of the PEDro scale for rating quality of randomized controlled trials. *Physical Therapy*, *83*(8), 713–721.

- Manini, T. M., & Clark, B. C. (2012). Dynapenia and aging: an update. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 67(1), 28–40. <https://doi.org/10.1093/gerona/qlr010>
- Nicola, F., & Catherine, S. (2011). Dose-response relationship of resistance training in older adults: a meta-analysis. *British journal of sports medicine*, 45(3), 233–234. <https://doi.org/10.1136/bjsm.2010.083246>
- Opdenacker, J., Delecluse, C., & Boen, F. (2011). A 2-year follow-up of a lifestyle physical activity versus a structured exercise intervention in older adults. *Journal of the American Geriatrics Society*, 59(9), 1602–1611. <https://doi.org/10.1111/j.1532-5415.2011.03551.x>
- Oswald, W. D., Gunzelmann, T., Rupprecht, R., & Hagen, B. (2006). Differential effects of single versus combined cognitive and physical training with older adults: the SimA study in a 5-year perspective. *European Journal of Ageing*, 3(4), 179–192.
- Perera, S., Mody, S. H., Woodman, R. C., & Studenski, S. A. (2006). Meaningful change and responsiveness in common physical performance measures in older adults. *Journal of the American Geriatrics Society*, 54(5), 743–749. <https://doi.org/10.1111/j.1532-5415.2006.00701.x>
- Pildal, J., Hróbjartsson, A., Jørgensen, K. J., Hilden, J., Altman, D. G., & Gøtzsche, P. C. (2007). Impact of allocation concealment on conclusions drawn from meta-analyses of randomized trials. *International journal of epidemiology*, 36(4), 847–857. <https://doi.org/10.1093/ije/dym087>
- Rubenstein, L. Z. (2006). Falls in older people: epidemiology, risk factors and strategies for prevention. *Age and Ageing*, 35 Suppl 2, ii37-ii41. <https://doi.org/10.1093/ageing/afl084>
- Sherrington, C., Michaleff, Z. A., Fairhall, N., Paul, S. S., Tiedemann, A., Whitney, J., . . . Lord, S. R. (2016). Exercise to prevent falls in older adults: an updated systematic review and meta-analysis. *British Journal of Sports Medicine*. doi: 10.1136/bjsports-2016-096547. [Epub ahead of print]
- Shumway-Cook, A., & Woollacott, M. H. (2007). *Motor control: translating research into clinical practice* (3<sup>rd</sup> ed.). Philadelphia: Lippincott Williams & Wilkins.
- Springer, B. A., Marin, R., Cyhan, T., Roberts, H., & Gill, N. W. (2007). Normative values for the unipedal stance test with eyes open and closed. *Journal of Geriatric Physical Therapy*, 30(1), 8–15.
- Stathi, A., McKenna, J., & Fox, K. R. (2010). Processes associated with participation and adherence to a 12-month exercise programme for adults aged 70 and older. *Journal of health psychology*, 15(6), 838–847. <https://doi.org/10.1177/1359105309357090>
- Steffen, T. M., Hacker, T. A., & Mollinger, L. (2002). Age- and gender-related test performance in community-dwelling elderly people: Six-Minute Walk Test, Berg Balance Scale, Timed Up & Go Test, and gait speeds. *Physical Therapy*, 82(2), 128–137.
- Steib, S., Schoene, D., & Pfeifer, K. (2010). Dose-response relationship of resistance training in older adults: a meta-analysis. *Medicine and Science in Sports and Exercise*, 42(5), 902–914. <https://doi.org/10.1249/MSS.0b013e3181c34465>
- Taylor, R. S., Dalal, H., Jolly, K., Zawada, A., Dean, S. G., Cowie, A., & Norton, R. J. (2015). Home-based versus centre-based cardiac rehabilitation. *The Cochrane Database of Systematic Reviews*, CD007130. doi: 10.1002/14651858.CD007130.pub3
- Thiebaud, R. S., Funk, M. D., & Abe, T. (2014). Home-based resistance training for older adults: a systematic review. *Geriatrics & Gerontology International*, 14(4), 750–757. <https://doi.org/10.1111/ggi.12326>

- Tinetti, M. E. (2003). Clinical practice. Preventing falls in elderly persons. *New England Journal of Medicine*, 348(1), 42–49. <https://doi.org/10.1056/NEJMcp020719>
- van Kan, G. A., Rolland, Y., Andrieu, S., Bauer, J., Beauchet, O., Bonnefoy, M., . . . Inzitari, M. (2009). Gait speed at usual pace as a predictor of adverse outcomes in community-dwelling older people an International Academy on Nutrition and Aging (IANA) Task Force. *The journal of nutrition, health & aging*, 13(10), 881–889.
- van Roie, E., Delecluse, C., Opendacker, J., Bock, K. de, Kennis, E., & Boen, F. (2010). Effectiveness of a Lifestyle Physical Activity Versus a Structured Exercise Intervention in Older Adults. *Journal of Aging & Physical Activity*, 18(3), 335–352.
- Watson, S. L., Weeks, B. K., Weis, L. J., Horan, S. A., & Beck, B. R. (2015). Heavy resistance training is safe and improves bone, function, and stature in postmenopausal women with low to very low bone mass: novel early findings from the LIFTMOR trial. *Osteoporosis International*, 26(12), 2889–2894. <https://doi.org/10.1007/s00198-015-3263-2>
- Wu, G., Keyes, L., Callas, P., Ren, X., & Bookchin, B. (2010). Comparison of telecommunication, community, and home-based Tai Chi exercise programs on compliance and effectiveness in elders at risk for falls. *Archives of Physical Medicine and Rehabilitation*, 91(6), 849–856. <https://doi.org/10.1016/j.apmr.2010.01.024>