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Effects of Core Instability Strength Training on Trunk Muscle Strength, Spinal Mobility, Dynamic Balance and Functional Mobility in Older Adults

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Key Words
Elderly · Gait · Muscle strength · Physical performance · Postural balance

Abstract

Background: Age-related postural misalignment, balance deficits and strength/power losses are associated with impaired functional mobility and an increased risk of falling in seniors. Core instability strength training (CIT) involves exercises that are challenging for both trunk muscles and postural control and may thus have the potential to induce benefits in trunk muscle strength, spinal mobility and balance performance. ***Objective:*** The objective was to investigate the effects of CIT on measures of trunk muscle strength, spinal mobility, dynamic balance and functional mobility in seniors. ***Methods:*** Thirty-two older adults were randomly assigned to an intervention group (INT; n = 16, aged 70.8 ± 4.1 years) that conducted a 9-week progressive CIT or to a control group (n = 16, aged 70.2 ± 4.5 years). Maximal isometric strength of the trunk flexors/extensors/lateral flexors (right, left)/rotators (right, left) as well as of spinal mobility in the sagittal and the coronal plane was measured before and after the intervention program. Dynamic balance (i.e. walking 10 m on an optoelectric walkway, the Functional Reach test) and functional mobility (Timed Up and Go test) were additionally tested. ***Results:*** Program compliance was excellent with participants of the INT group completing 92% of the training sessions. Significant group × test interactions were found for the maximal isometric strength of the trunk flexors (34%, $p < 0.001$), extensors (21%, $p < 0.001$), lateral flexors (right: 48%, $p < 0.001$; left: 53%, $p < 0.001$) and left rotators (42%, $p < 0.001$) in favor of the INT group. Further, training-related improvements were found for spinal mobility in the sagittal (11%, $p < 0.001$) and coronal plane (11%, $p = 0.06$) directions, for stride velocity (9%, $p < 0.05$), the coefficient of variation in stride velocity (31%, $p < 0.05$), the Functional Reach test (20%, $p < 0.05$) and the Timed Up and Go test (4%, $p < 0.05$) in favor of the INT group. ***Conclusion:*** CIT proved to be a feasible exercise program for seniors with a high adherence rate. Age-related deficits in measures of trunk muscle strength, spinal mobility, dynamic balance and functional mobility can be mitigated by CIT. This training regimen could be used as an adjunct or even alternative to traditional balance and/or resistance training.

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Introduction

A major challenge for the societies of western industrialized countries is a tremendously aging population [1]. With an increasing number of older people, per capita health expenditures rise due to a higher prevalence of sustaining chronic diseases (e.g., osteoporosis) and/or fall-related injuries (e.g., proximal femur fracture) [2, 3]. In fact, direct annual costs for the treatment of proximal femur fractures amounted to EUR 2.8 billion in Germany in 2004. Due to population aging, treatment costs for this typical fall injury are estimated to increase to EUR 3.85 billion in 2030 [4].

What makes older adults prone to falling as compared to young adults? The aging process results in various deteriorations in the central nervous (e.g., loss of sensory and motor neurons), the neuromuscular (e.g., atrophy of particularly type II muscle fibers), and the bony system (e.g., osteoporosis) that are associated with a hyperkyphotic (i.e. flexed) posture, impaired balance control and losses in strength/power. Recently, Katzman et al. [5] reported that age-related hyperkyphosis is associated with impaired mobility in community-dwelling older women. Further, Callisaya et al. [6] observed that different markers of dynamic balance (e.g., gait speed, stride-to-stride variability) are related to an increased risk of sustaining multiple falls in individuals aged 60–86 years. Finally, Kasukawa et al. [7] found significantly lower levels of maximal back extensor strength in elderly fallers as compared to non-fallers with an age range of 60–92 years. The findings of Katzman et al. [5], Callisaya et al. [6] and Kasukawa et al. [7] indicate that training-induced improvements in postural alignment, dynamic balance and trunk muscle strength may represent promising fall-preventive exercise strategies.

Traditionally, lower extremity balance and/or resistance training have been conducted for fall-preventive purposes in older adults [for a review, see ref. 8, 9]. More recently, particularly the lay literature has promoted the importance of core strength for the successful performance of everyday and sports-related activities [10]. As a consequence, researchers, specifically from the field of sports performance, became interested in the topic and established a general understanding of the core concept. According to Behm et al. [11], the core can be thought of as the kinetic link that facilitates the transfer of torques and angular momentum between the lower and upper extremities during the performance of sports skills, occupational skills, fitness activities and activities of daily living. Kibler et al. [12] argued that the core is especially important in everyday and sports-related activities because it provides proximal stability for distal mobility. Preliminary studies reinforce and extend these hypotheses by showing that there is an association between trunk muscle strength (trunk extensor strength) and balance (unipedal stance test) as well as functional mobility (Short Physical Performance Battery, Berg Balance Scale) in community-dwelling older adults with a mean age of 76 years [13]. Further, Hicks et al. [14] investigated whether trunk muscle composition is a predictor of functional mobility in community-dwelling older adults (age range 70–79 years). It was found that older adults with poor trunk muscle composition exhibit reduced functional mobility 3 years later. The authors concluded that improving trunk muscle composition may be an important approach to maintain function and potentially reduce balance and functional mobility impairments. Given these findings [5, 13, 14], it seems plausible to argue that core strength training may have the potential to improve trunk muscle strength, postural alignment, balance and functional mobility in older adults.

Notably, the performance of several everyday activities occurs on relatively unstable surfaces (e.g., walking on cobblestone pavement/trails/sand). Thus, according to the principle of training specificity, training must attempt to closely address the demands of everyday tasks. Further, Borghuis et al. [15] stated that the integration of proprioceptive demands in training (e.g., using unstable surfaces) leads to increased trunk muscle activity, thereby improving trunk muscle strength, balance and functional mobility. To the authors' knowledge, there is no study available that investigated the effects of core instability strength training (CIT) on measures of trunk muscle strength, spinal mobility, balance and functional mobility in older adults.

Thus, the objective of this study was to examine the impact of CIT on these measures in healthy seniors. Based on the available but preliminary literature [13, 14], it is expected that the combination of strength and instability training has the potential to improve variables of trunk muscle strength, spinal mobility, balance and functional mobility in older adults.

Methods

Participants

Thirty-two community-dwelling older adults between the ages of 63 and 80 years gave written informed consent to participate in the study after experimental procedures were explained. Study participants were recruited by posting flyers at public insti-

Table 1. Baseline characteristics by group and sex

	INT			CON		
	females (n = 8)	males (n = 8)	all (n = 16)	females (n = 9)	males (n = 7)	all (n = 16)
Age, years	71.1 (3.8)	70.6 (4.7)	70.8 (4.1)	70.9 (4.1)	69.3 (5.1)	70.2 (4.5)
Body height, cm	163.7 (3.7)	173.5 (8.0)	168.6 (7.9)	162.3 (4.6)	172.8 (4.0)	166.9 (6.9)
Body mass, kg	63.8 (9.0)	79.3 (8.3)	71.5 (11.6)	66.3 (9.5)	80.4 (12.1)	72.4 (12.6)
Body mass index, kg/m^2	23.8 (3.3)	26.3 (1.7)	25.1 (2.9)	25.2 (3.8)	26.9 (4.2)	26.0 (3.9)
MMSE	28.0 (1.1)	28.4 (1.4)	28.2 (1.2)	28.1 (1.4)	27.7 (1.4)	27.9 (1.3)
CDT	all participants were classified as non-pathological					
Physical activity, h/week	10.1 (4.4)	14.0 (9.7)	12.0 (7.5)	13.5 (4.5)	14.5 (10.2)	13.9 (7.2)

Values are means with SDs in parentheses. No group by sex baseline differences were detected ($p > 0.05$).

tutions (e.g., grocery store, library) and by publishing advertisements in local newspapers. Participants' baseline 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 conduct a CIT program or to perform trunk muscle strength, spinal mobility, dynamic balance and functional mobility tests. The participants were capable of walking independently without any assistive device and they had no prior experience with CIT and the applied tests. Further, only cognitively healthy older adults were eligible to participate in the study [i.e. non-pathological rating in the Clock Drawing Test (CDT) and a Mini Mental State Examination (MMSE) score of ≥24]. Participants were randomly assigned into an intervention (INT) group and a control (CON) group. The randomization process was done using Research Randomizer, a program published on a publicly accessible official website (www.randomizer.org). Local ethical permission was given, and all experiments were conducted according to the latest version of the Declaration of Helsinki.

Core Instability Strength Training

Participants of the INT group conducted a CIT program over a period of 9 weeks (2 times per week) with a total of 18 sessions. Each training session lasted 60 min, starting with a 10-min warm-up program mainly consisting of core strength exercises at moderate intensities and ending with a 5-min cool-down program (stretching). The intervention program was given by an expert on core strength training (Master's degree in exercise science, license for conducting exercise programs with older adults), and participants of CIT were separated in 2 exercise groups in order to keep the participant-to-instructor ratio small (1 instructor for 8 seniors). Our conditioning program complies with an example for an evidence-based core strength training program [16]. More specifically, CIT was always conducted on fitness mats using unstable training devices (e.g., balance pads, Swiss balls) but not resistance training machines. Throughout the training sessions, participants were always in supine, prone, quadruped and side-lying positions on the fitness mat to avoid continuous position changes (from standing to lying/sitting and vice versa) which are often felt as uncomfortable by older adults. Every single CIT session consisted of frontal, dorsal, rotational and lateral core exercises. For an example, see figure 1a–i. Training intensity was progressively and individually increased over the 9-week training program by modulating lever lengths, range of motion, movement velocity (isometric, dynamic) and the level of stability/instability. Due to the relatively high proportion of type I fibers, the core musculature might respond particularly well to multiple sets that involve many repetitions (e.g., >15 per set) [11]. Thus, our participants performed 3–4 sets per exercise with 15–20 s contraction time (isometric condition) or 15–20 repetitions (dynamic condition). The rest between sets comprised 30 s and between exercises 2–3 min. Due to the small participant-to-instructor ratio, CIT was safe without any intervention-related risk of injury. The participants of the CON group maintained their normal physical activities throughout the experimental period (i.e. they did not take up any new sports-related activities during the intervention period).

Testing Procedure

Upon entering our biomechanical laboratory, all participants were kindly asked to answer the questions of three different questionnaires (Freiburg questionnaire for everyday and sports-related activities©, MMSE and CDT). Thereafter, participants received standardized verbal instructions regarding the test procedure with a visual demonstration of the trunk muscle strength, spinal mobility, dynamic balance and functional mobility 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 [17]. Pre- and post-training tests included (1) measurement of dynamic balance and functional mobility in a randomized sequence on a moveable sliding apparatus and an optoelectric walkway, (2) the analysis of spinal mobility in the sagittal (SAP) and the coronal (CRP) plane using the Medi-Mouse© system, and (3) 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. This testing sequence was applied in order to keep the effects of neuromuscular fatigue minimal.

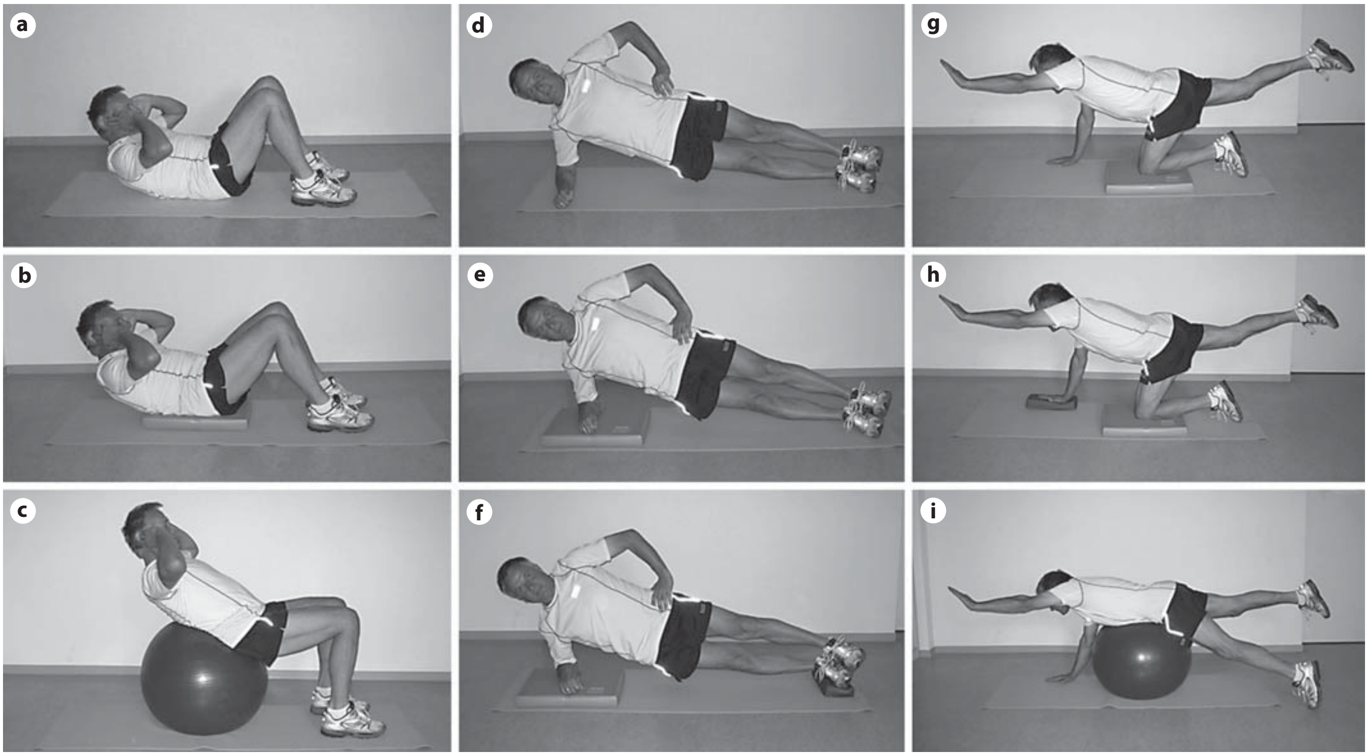

Fig. 1. Participant progressively performing curl up (**a–c**), side bridge (**d–f**) and quadruped (**g–i**) exercises.

Testing Material

Dynamic Balance Testing

Test circumstances (e.g., room illumination, temperature, noise) were in accordance with recommendations for posturographic testing [18]. Dynamic balance was analyzed by means of the Functional Reach test (FRT) [19]. For this purpose, a moveable sliding apparatus was constructed that allowed the determination of the maximal distance one can reach forward beyond arm's length while maintaining a fixed base of support in the standing position [20]. Three test trials were conducted and averaged for further data analysis. The FRT showed excellent test-retest reliability, with an intraclass correlation coefficient (ICC) of 0.92 in older adults [19]. In addition, calculations from our own data indicated an excellent ICC value of 0.77. Validity of the FRT has been shown by Newton [21] when testing healthy community-dwelling older adults.

The walking pattern was determined during steady-state walking on an instrumented 10-m walkway using the OptoGait© System (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-meter walkway to allow sufficient distance to accelerate to and decelerate from a steady state of ambulation across the walkway. The OptoGait 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 is monitored at 1,000 Hz, enabling spatial and temporal gait data to be collected. Hausdorff et al. [22] reported that temporal and spatial parameters of gait are important mobility markers in community-dwelling older adults. Thus, in a first step, means and standard deviations (SDs) of stride velocity were computed. Stride velocity (cm/s) was calculated as stride length divided by stride time. To determine gait variability, the coefficient of variation (CV) was analyzed for stride velocity according to the following formula [(SD/mean) × 100] and used as outcome measures [23]. The smaller the CV value, the more stable the walking pattern. Granacher et al. [24] reported that ICC values for the calculated gait parameters were above 0.75.

Functional Mobility Testing

The Timed Up and Go Test (TUG) was used as described by Podsiadlo and Richardson [25]. Participants were asked to perform the TUG at their self-selected normal speed. One test trial was performed. Time was recorded with a stopwatch to the nearest 0.01 s. 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. The TUG showed excellent test-retest reliability (ICC = 0.99) in older adults [25].

Spinal Mobility Testing

Spinal mobility was determined using the MediMouse system, a hand-held, computer-assisted electromechanical device for measuring the spinal curvature in various postures [26]. 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 SAP (maximal extension to flexion) and the range of flexion in the CRP (maximal left to right flexion) were determined and used as outcome measures. ICC values were calculated for spinal mobility in the SAP (ICC = 0.85) and the CRP (ICC = 0.85). In addition, it was shown that the MediMouse system has acceptable validity (assessed by radiography) in adults [27].

Trunk Muscle Strength Testing

MIS of the trunk muscles was measured using 4 Norsk trunk testing machines (Pingsheim, Germany) that allowed the analysis of 6 different movement directions [flexion, extension, rotation in the transversal plane (right, left) and lateral bending (right, left)] [28]. MIS was defined as the maximal voluntary strength (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. The exact position of each participant was documented and saved so that it was identical during pre- and post-training tests. All participants performed 3 maximal isometric contractions lasting 3–4 s 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 3 test trials was used as an outcome measure. Bak et al. [29] reported excellent inter- and intrasession reliability in all movement directions. In addition, ICC values were calculated for MIS of the trunk muscles ranging from 0.89 to 0.96.

Questionnaire

The Freiburg questionnaire for everyday and sports activities [16] 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 and 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 [16].

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 sore revealed a correlation coefficient of r = 0.78 [17]. An MMSE total score of <20 separates patients with dementia or functional psychosis from cognitively independently functioning participants and those with anxiety neurosis or personality disorder.

The CDT is a sensitive screening test for the evaluation of executive function [30]. 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 end, they had to write down in digital form. Depending on the study consulted, inter-rater reliability for the CDT ranges between 75.4 and 99.6% [30]. Test-retest reliability can be classified as high, with an r value of 0.90 [31]. Cross-correlation with the MMSE revealed a correlation coefficient of $r > 0.50$ [32]. As a result, the test distinguishes between pathological and normal test performance.

Statistical Analyses

Data are presented as group mean values ± SD. A multivariate analysis of variance was used to detect differences between study groups in all baseline variables. Trunk muscle strength, spinal and functional mobility as well as dynamic balance parameters were analyzed in separate 2 (groups: INT and CON) × 2 (tests: before and after training) analysis of variance with repeated measures on test. Post hoc tests with the Bonferroni-adjusted α were conducted to identify the comparisons that were statistically significant. The classification of effect sizes (f) was determined by calculating partial η^2_p. The effect size is the measure of the effectiveness of a treatment and it helps to determine whether a statistically significant difference is a difference of practical concern. f = 0.10 indicate small, f = 0.25 medium and f = 0.40 large effects [26]. An a priori power analysis [33] with an assumed type I error of 0.05 and a type II error rate of 0.20 (80% statistical power) was conducted for measures of trunk muscle strength [34] and revealed that 16 persons per group would be sufficient for finding statistically significant interaction effects. All analyses were performed using Statistical Package for Social Sciences version 20.0. The significance level was set at $p < 0.05$.

Results

At baseline, all subjects met the inclusion criteria (e.g., MMSE, CDT) for participating in this study. The investigated results in the MMSE and the CDT indicate that the older adults of this study were cognitively healthy (table 1). Findings regarding the Freiburg questionnaire for everyday and sports activities reveal that our participants can be classified as physically active (table 1). All subjects received treatment or control conditions as allocated. Participants in the INT group completed the CIT and none reported any training-related injury. The INT group showed a high attendance rate during training sessions with 92%. Table 2 displays means and SDs for all analyzed variables. Overall, there were no statistically significant differences in pre-training values between the 2 groups.

Trunk Muscle Strength

The analysis showed statistically significant group × test interactions for the parameters MIS for the flexors/extensors, the lateral flexors (right, left) and the rotators (left but not right) (table 2). Effect sizes ranged between f = 0.23 and 1.02. Post hoc analysis found that participants in the INT group significantly increased their trunk muscle strength over the training period (all $p \leq 0.05$, Δ21–53%) while the participants in the CON group showed no significant changes.

Table 2. Outcome measures (ANOVA with repeated measures on test)

Measure	INT (n = 16)			CON (n = 16)			p value	
	before	after	Δ, %	before	after	Δ, %	test	group × test
Trunk strength								
MIS of the extensors, Nm	165.9 (72.0)	201.5 (67.2)	+21	164.3 (55.7)	163.8 (54.3)	–0.3	0.000 [0.71]	0.000 [0.73]
MIS of the flexors, Nm	80.4 (34.8)	107.4 (46.4)	+34	86.7 (46.4)	87.6 (41.4)	+1	0.000 [0.94]	0.000 [0.88]
MIS of the lateral flexors left, Nm	81.7 (38.6)	125.1 (51.4)	+53	97.7 (40.8)	104.7 (48.1)	+7	0.000 [0.96]	0.001 [0.69]
MIS of the lateral flexors right, Nm	64.8 (28.8)	96.0 (37.1)	+48	74.5 (32.3)	73.3 (32.3)	–2	0.000 [0.95]	0.000 [1.02]
MIS of the rotators right, Nm	53.9 (31.6)	74.6 (39.7)	+38	67.7 (38.2)	79.9 (47.4)	+18	0.000 [0.88]	0.223 [0.23]
MIS of the rotators left, Nm	56.4 (29.7)	80.0 (37.6)	+42	68.1 (36.7)	67.1 (38.3)	–2	0.000 [0.73]	0.000 [0.80]
Spinal mobility								
SAP spinal mobility, °	122.1 (18.2)	135.1 (17.8)	+11	132.6 (13.6)	126.3 (15.8)	–5	0.021 [0.44]	0.000 [1.29]
CRP spinal mobility, °	51.6 (13.0)	57.4 (10.6)	+11	49.6 (12.5)	48.1 (13.6)	–3	0.267 [0.21]	0.058 [0.36]
Dynamic balance								
Stride velocity, cm/s	141.1 (14.3)	153.2 (14.1)	+9	141.9 (14.8)	142.4 (18.9)	+0.4	0.014 [0.48]	0.022 [0.44]
Stride velocity CV, %	3.5 (2.2)	2.4 (0.9)	+31	2.6 (1.1)	2.9 (1.7)	–11.5	0.190 [0.25]	0.033 [0.41]
FRT, cm	31.8 (5.1)	38.3 (3.5)	+20	32.3 (5.7)	33.8 (4.8)	+5	0.000 [0.95]	0.003 [0.59]
Functional mobility								
TUG, s	9.5 (1.0)	9.1 (0.6)	+4	9.4 (0.8)	9.8 (0.8)	–4	0.807 [0.04]	0.042 [0.39]

Values are means with SDs in parentheses. Figures in brackets are effect sizes. No group baseline differences were detected; p > 0.05.

Spinal Mobility

The analysis showed statistically significant group × test interactions for both spinal mobility parameters (table 2). Effect sizes ranged between f = 0.36 and 1.29. Post hoc analysis found that participants in the INT group significantly increased their spinal mobility over the training period (SAP: $p < 0.01$, Δ11%; CRP: $p = 0.06$, Δ11%) while the participants in the CON group showed no significant changes.

Dynamic Balance

The analysis showed statistically significant group × test interactions for the parameters stride velocity and stride velocity CV as well as for FRT performance (table 2). Effect sizes ranged between f = 0.41 and 0.59. Post hoc analysis found that participants in the INT group significantly increased their dynamic balance over the training period (all $p < 0.05$, Δ9–31%) while the participants in the CON group showed no significant changes.

Functional Mobility

The analysis showed a statistically significant group × test interaction for the TUG performance resulting in an effect size of f = 0.39 (table 2). Post hoc analysis found that participants in the INT group significantly increased their functional mobility over the training period ($p < 0.05$, Δ4%) while the participants in the CON group showed no significant changes.

Discussion

This is the first study that investigated the impact of CIT on measures of trunk muscle strength, spinal and functional mobility as well as on balance in healthy and physically active seniors. Given that age-related changes in postural alignment, dynamic balance, functional mobility and back extensor strength are associated with mobility limitations and an increased fall risk in older adults [5–7], training-induced improvements in posture, balance, functional mobility and core strength may represent promising fall-preventive exercise strategies. Nine weeks of progressive CIT resulted in (1) significant improvements in muscle strength of the trunk flexors, extensors, rotators and lateral flexors, (2) a significantly enhanced spinal mobility in the SAP and the CRP directions, and (3) significant improvements in dynamic balance (stride velocity, CV in stride velocity, FRT) and functional mobility (TUG).

The present findings are related to results reported in the literature. In a preliminary study, Petrofsky et al. [35] investigated the effects of a core strength training program using a commercial exercise device (the 6 Second Abs Machine) on MIS of the abdominal and back muscles in older adults aged 61–82 years. After the 4-week training period (3 training sessions/week), significant strength increases in abdominal ($p < 0.01$, Δ36%) and back muscles ($p < 0.01$, Δ33%) were observed. However, these findings have to be interpreted with caution given that no control group was included in the study design. Nevertheless, the training-related improvements in trunk muscle strength (all $p \leq 0.05$, Δ21–53%) in the present study substantiate the findings of Petrofsky et al. [35]. In a recent and controlled study, Irez et al. [36] investigated the impact of a 12-week Pilates exercise training (3 training sessions/week) on maximal isometric hip muscle strength in women aged 65 years and older. The authors reported a significant increase in hip muscle strength following training ($p < 0.05$, Δ40%). Finally, Carter et al. [34] observed significant improvements in the static back endurance test ($p < 0.05$, Δ30%) and the side bridge test ($p < 0.05$, Δ57%) following 10 weeks of progressive stability ball training (2 training sessions/week) for the trunk muscles in sedentary subjects with a mean age of 36 ± 8 years for the INT group and of 40 ± 10 years for the CON group, respectively. Notably, the use of unstable exercise devices (e.g., Swiss Balls, balance pads) in the study of Carter et al. [34] and in our study proved to be effective in promoting trunk muscle strength in sedentary middle-aged and older adults.

Spinal mobility is an important prerequisite to perform everyday activities, particularly in older adults. In fact, in an early study, Bergstrom et al. [37] found moderate to strong correlations between loss of spinal flexibility (thoracic range of motion) and difficulty in climbing stairs or using public transportation in a cohort of 79-year-old adults. Schenkman et al. [38] demonstrated associations between spinal rotation and balance performance (FRT) as well as several functional tasks (number of steps and time to accomplish a 360° turn, timed movement from a supine to a sitting position) in 20–40, 65–74 and ≥75 year olds. These correlative analyses indicate that training-related improvements in spinal mobility could have an effect on postural control and performance in functional tasks. As a matter of fact, the results of the present study (i.e. enhanced spinal mobility in SAP and CRP directions) and findings from other research groups [36, 39] confirm this hypothesis. Both, Irez et al. [36] and Kuo et al. [39] investigated the effects of Pilates exercise on spinal mobility in adults aged 60 years and older. The authors reported that training resulted in improved performance in the sit-and-reach test ($p < 0.05$, Δ24%) [36] as well as in decreased thoracic flexion during standing ($p < 0.05$, Δ2%) and increased lumbar extension during sitting ($p < 0.05$, Δ3%) [39].

Age-related changes in postural control and functional mobility can amongst others be attributed to cognitive impairment [40], visual, vestibular and proprioceptive dysfunctions [41], as well as muscle weakness [42]. Some of these aging processes (cognitive impairment, vestibular and proprioceptive dysfunctions, muscle weakness) can be mitigated by adequate training programs [for a review, see ref. 8]. CIT could have the potential to induce adaptive processes specifically in the neuromuscular system that enhances balance performance and functional mobility in older adults. In fact, Staron et al. [43] described a number of neural adaptations following core strength training that included more efficient neural recruitment patterns, faster nervous system activation, improved synchronization of motor units and a lowering of neural inhibitory reflexes. However, due to methodological limitations (lack of electrophysiological tests), this study cannot elucidate whether improvements in the central nervous system and the neuromuscular system occurred following CIT. Nevertheless, on a behavioral level, we were able to show that 9 weeks of progressive CIT resulted in significant improvements in dynamic balance (FRT, stride velocity, stride velocity CV) and functional mobility (TUG). This finding is in accordance with the literature [35, 44–46]. In fact, Petrofsky and colleagues [35] demonstrated significant improvements in maximum reach in the forward ($p < 0.01$, Δ46%), right ($p < 0.01$, Δ22%) and left ($p < 0.01$, Δ43%) directions after 4 weeks of core strength training (3 training sessions/week) in adults aged 61–82 years. Further, in a randomized controlled study, Bird et al. [44] recently investigated the effects of Pilates exercise on measures of static/dynamic balance and functional mobility in community-dwelling older adults with a mean age of 67 ± 5 years. After the 5-week training program (2 training sessions/week), the authors found significant reductions in center-of-pressure displacements in the mediolateral direction during bipedal stance on foam ground with eyes opened ($p = 0.01$, Δ17%) and eyes closed ($p < 0.01$, Δ22%). In addition, training-related performance enhancements were observed for the TUG ($p < 0.01$, Δ6%) and the Four Square Step Test ($p = 0.01$, Δ7%). In a similar approach, Kaesler et al. [45] reported significant improvements in different measures of static and dynamic balance (e.g., postural sway during standing on firm/foam ground with eyes opened/closed) and functional mobility (e.g., TUG) ranging from 8 to 27% (all $p < 0.05$) following 8 weeks of Pilates exercise (2 training sessions/week) in community-dwelling men and women aged 66–71 years. Finally, Newell et al. [46] studied the impact of an 8-week community-based and supervised Pilates training (1 training session/week) on measures of dynamic balance in a group of elderly subjects with an age range of 60–76 years. Training resulted in significant improvements in mean walking speed ($p < 0.05$, $\Delta 27\%$), step cycle ($p < 0.05$, $\Delta 13\%$) and step length ($p < 0.05$, $\Delta 24\%$).

It has frequently been shown that the effects of traditional machine-based resistance training for the lower extremities are restricted to measures of strength/power of the trained muscles but cannot be transferred to balance performance and functional mobility [for a review, see ref. 47]. In contrast, it has been demonstrated that core strength training or Pilates exercise has the potential to induce improvements in trunk muscle strength, spinal mobility as well as in balance performance and functional mobility in older adults. What makes the trunk muscles so special that improved core stability (i.e. combination of core strength and spinal mobility) results in better balance performance and functional mobility? From a biomechanical perspective, a stable core facilitates the transfer of torques and angular momentum between the lower and upper extremities during the performance of everyday tasks. In other words, it provides proximal stability for distal mobility [12]. From a neurophysiological perspective, there is evidence that during normal human movement, trunk muscle activations (e.g., musculus transversus abdominis) are organized well ahead (110 ms) in anticipation of movement or perturbation to balance in healthy adults with a mean age of 21 ± 2 years [48]. Hodges and Richardson [48] argued that this anticipatory muscle activation helps stiffening the spine to provide a foundation for functional movements.

When translating this theoretical framework into exercise practice, it could be hypothesized that continuous and progressive conditioning stimuli for the trunk muscles (by applying core strength training) and the proprioceptors (by including unstable devices in core strength training) may result in improved dynamic balance and functional mobility in older adults.

This study has some limitations that need to be addressed. First, due to the design of the present study, it is not possible to elucidate additional effects of unstable elements integrated in core strength training. Thus, future studies should investigate the effects of traditional core strength training or balance training versus CIT on measures of trunk muscle strength, postural control and spinal mobility in a comparative approach. Second, our recruitment methods (flyers, newspaper advertisements) may have caused selection bias. Thus, caution is needed when translating the present results to other senior populations (e.g., less physically active).

In summary, this is the first controlled study that proved the feasibility and effectiveness of a progressive CIT on measures of trunk muscle strength, spinal mobility, dynamic balance and functional mobility in healthy older adults. Given that program compliance was high (92%) and no training-related injuries were reported, it appears that this training modality can be used as an adjunct or even alternative to traditional balance and/or resistance training programs for older adults. Further, CIT is easy to administer in group or individual fall preventive or rehabilitative intervention programs because little equipment and space is needed to conduct this exercise modality. Future studies need to elucidate whether the integration of unstable devices in core strength training has an additional effect on measures of trunk muscle strength, spinal mobility, balance and functional mobility as compared to stable core strength training or Pilates exercise. The design of the present study did not allow answering this research question.

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