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POSTURAL CONTROL IN YOUTH: FROM PERFORMANCE TO NEURAL CORRELATES

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Hereby, I declare that this thesis entitled “Postural control in youth: From performance to neural correlates” or parts of the thesis have not yet been submitted for a doctoral degree to this or any other institution neither in identical nor in similar form. The work presented in this thesis is the original work of the author. I did not receive any help or support from commercial consultants. All parts or single sentences, which have been taken analogously or literally from other sources, are identified as citations. Additionally, significant contributions from co-authors to the articles of this cumulative dissertation are acknowledged in the authors’ contribution section.

Place, Date

Arnd Sebastian Gebel

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List of publications

The present cumulative thesis is based on the following publications.

Publication I	Gebel A, Lesinski M, Behm DG, Granacher U (2018). Effects and dose-response relationship of balance training on balance performance in youth: A systematic review and meta-analysis. *Sports Medicine*, 48(9), 2067-2089. doi:10.1007/s40279-018-0926-0
Publication II	Gebel A, Lüder B, Granacher U (2019). Effects of increasing balance task difficulty on postural sway and muscle activity in healthy adolescents. *Frontiers in Physiology*, 10:1135. doi: 10.3389/fphys.2019.01135
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Abstract

Background and objectives: The intricate interdependencies between the musculoskeletal and neural systems build the foundation for postural control in humans, which is a prerequisite for successful performance of daily and sports-specific activities. Balance training (BT) is a well-established training method to improve postural control and its components (i.e., static/dynamic steady-state, reactive, proactive balance). The effects of BT have been studied in adult and youth populations, but were systematically and comprehensively assessed only in young and old adults. Additionally, when taking a closer look at established recommendations for BT modalities (e.g., training period, frequency, volume), standardized means to assess and control the progressive increase in exercise intensity are missing. Considering that postural control is primarily neuronally driven, intensity is not easy to quantify. In this context, a measure of balance task difficulty (BTD) appears to be an auspicious alternative as a training modality to monitor BT and control training progression. However, it remains unclear how a systematic increase in BTD affects balance performance and neurophysiological outcomes. Therefore, the primary objectives of the present thesis were to systematically and comprehensively assess the effects of BT on balance performance in healthy youth and establish dose-response relationships for an adolescent population. Additionally, this thesis aimed to investigate the effects of a graded increase in BTD on balance performance (i.e., postural sway) and neurophysiological outcomes (i.e, leg muscle activity, leg muscle coactivation, cortical activity) in adolescents.

Methods: Initially, a systematic review and meta-analysis on the effects of BT on balance performance in youth was conducted per the Preferred Reporting Items for Systematic Reviews and Meta-Analysis statement guidelines. Following this complementary analysis, thirteen healthy adolescents (3 female/ 10 male) aged 16-17 years were enrolled for two cross-sectional studies. The participants executed bipedal balance tasks on a multidirectional balance board that allowed six gradually increasing levels of BTD by narrowing the balance boards' base of support. During task performance, two pressure sensitive mats fixed on the balance board recorded postural sway. Leg muscle activity and leg muscle coactivation were assessed via electromyography while electroencephalography was used to monitor cortical activity.

Results: Findings from the systematic review and meta-analysis indicated moderate-to-large effects of BT on static and dynamic balance performance in youth (static: weighted mean standardized mean differences [SMD_{wm}] = 0.71; dynamic: SMD_{wm} = 1.03). In adolescents, training-induced effects were moderate and large for static ($\text{SMD}_{\text{wm}} = 0.61$) and dynamic ($\text{SMD}_{\text{wm}} = 0.86$) balance performance, respectively. Independently (i.e. modality-specific) calculated dose-response relationships identified a training period of 12 weeks, a frequency of two training sessions per week, a total of 24-36 sessions, a duration of 4-15 minutes, and a total duration of 31-60 minutes as the training modalities with the largest effect on overall balance performance in adolescents. However, the implemented meta-regression indicated that none of these training modalities ($R^2 = 0\%$) could predict the observed performance-increasing effects of BT.

Results from the first cross-sectional study revealed that a gradually increasing level of BTD caused increases in postural sway ($p < 0.001$; $d = 6.36$), higher leg muscle activity ($p < 0.001$; $2.19 < d < 4.88$), and higher leg muscle coactivation ($p < 0.001$; $1.32 < d < 1.41$). Increases in postural sway and leg muscle activity were mainly observed during low and high levels of task difficulty during continuous performance of the respective balance task. Results from the second cross-sectional study indicated frequency-specific increases/decreases in cortical activity of different brain areas ($p < 0.005$; $0.92 < d < 1.80$) as a function of BTD. Higher cortical activity within the theta frequency band in the frontal and central right brain areas was observed with increasing postural demands. Concomitantly, activity in the alpha-2 frequency band was attenuated in parietal brain areas.

Conclusion: BT is an effective method to increase static and dynamic balance performance and, thus, improve postural control in healthy youth populations. However, none of the reported training modalities (i.e., training period, frequency, volume) could explain the effects on balance performance. Furthermore, a gradually increasing level of task difficulty resulted in increases in postural sway, leg muscle activity, and coactivation. Frequency and brain area-specific increases/decreases in cortical activity emphasize the involvement of frontoparietal brain areas in regulatory processes of postural control dependent on BTD. Overall, it appears that increasing BTD can be easily accomplished by narrowing the base of support. Since valid methods to assess and quantify BT intensity do not exist, increasing BTD appears to be a very useful candidate to implement and monitor progression in BT programs in healthy adolescents.

Keywords: adolescents, balance, postural sway, muscle activity, cortical activity, balance training, task difficulty

Zusammenfassung

Hintergrund und Ziele: Die postural Kontrolle des Menschen basiert auf der komplexen Interaktion von muskuloskelettalem und neuralem System. Gleichzeitig bildet sie eine Grundvoraussetzung für die erfolgreiche Ausführung von sport-spezifischen Aktivitäten sowie denen des täglichen Lebens. Das Gleichgewichtstraining ist eine gut etablierte Trainingsmethode, welche der Verbesserung der posturalen Kontrolle und seiner Komponenten (statisch/dynamisch-kontinuierliches, reaktives, proaktives Gleichgewicht) dient. Die Effekte dieser Trainingsmethode wurden bereits bei gesunden jungen und älteren Erwachsenen systematisch untersucht, wurde aber bisher bei Kindern und Jugendlichen versäumt. Bei genauerer Betrachtung der gängigen Trainingsempfehlungen zur Ausgestaltung der Trainingsvariablen (z.B., Dauer, Frequenz, Umfang) für das Gleichgewichtstraining fällt auf, dass momentan keine standardisierte Methode existiert, welche es ermöglicht die Intensität des Gleichgewichtstrainings zu erfassen. Da die posturale Kontrolle primär neuronal gesteuert ist, lässt sich die Intensität einzelner Gleichgewichtsübungen bzw. eines ganzen Trainings schwer bestimmen. Der Schwierigkeitsgrad einer Gleichgewichtsaufgabe könnte daher eine aussichtsreiche Alternative als Trainingsvariable zur Steuerung der Trainingsbelastung im Rahmen des Gleichgewichtstrainings sein. Bisher ist jedoch unklar wie sich eine graduelle Steigerung der Aufgabenschwierigkeit auf die Gleichgewichtsleistung sowie neurophysiologische Parameter auswirkt. Das primäre Ziel dieser Doktorarbeit ist es daher, die Effekte des Gleichgewichtstrainings auf die Gleichgewichtsleistung von gesunden Kindern und Jugendlichen systematisch zu untersuchen und zu aggregieren sowie entsprechende Dosis-Wirkungs-Verhältnisse für Jugendliche herauszuarbeiten. Des Weiteren soll der Einfluss einer graduellen Steigerung des Schwierigkeitsgrades einer Gleichgewichtsaufgabe auf die Gleichgewichtsleistung (d.h., posturale Schwankung) sowie neurophysiologische Parameter (d.h., Aktivität und Koaktivität der Beinmuskulatur, kortikale Aktivität) von Jugendlichen untersucht werden.

Methoden: Zu Beginn wurde ein systematischer Überblicksbeitrag mit Meta-Analyse angefertigt, welcher, basierend auf den PRISMA Richtlinien, die Effekte des Gleichgewichtstrainings auf die Gleichgewichtsleistung von Kindern und Jugendlichen zusammenfasste und quantifizierte. Im Anschluss an diese Übersichtsarbeit wurden zwei Querschnittsuntersuchungen durchgeführt. An beiden Untersuchungen nahmen 13 gesunde Jugendliche im Alter von 16 – 17 Jahren (3 weiblich/ 10 männlich) teil. Im Rahmen der experimentellen Untersuchung führten die Jugendlichen eine Gleichgewichtsaufgabe in bipedalem Stand auf einem multidirektionalen Balance Board aus. Der Schwierigkeitsgrad der Gleichgewichtsaufgabe wurde hierbei mittels Verkleinerung der Unterstützungsfläche des Balance Boards über sechs Stufen graduell gesteigert. Während der Aufgabenausführung wurde die posturale Schwankung mittels zweier drucksensitiver Messmatten erfasst. Die Beinmuskelaktivität und -koaktivität sowie die kortikale Aktivität wurden mittels Elektromyographie beziehungsweise Elektroenzephalographie aufgenommen.

Ergebnisse: Insgesamt hat Gleichgewichtstraining einen moderaten bis großen Einfluss auf die statische und dynamische Gleichgewichtsleistung von Kindern und Jugendlichen (statisch: gewichtete mittlere standardisierte Mittelwertsdifferenz [SMDwm] = 0,71; dynamisch: SMDwm = 1,03). Eine altersspezifische Subgruppenanalyse für Jugendliche wies mittlere Trainingseffekte für das statische (SMDwm = 0,61) sowie große für das dynamische Gleichgewicht (SMDwm = 0,86) aus. Unabhängig (d.h., für jede Trainingsvariable spezifisch) berechnete Dosis-Wirkungs-Beziehungen zeigten, dass eine Interventionsdauer von 12 Wochen, eine Trainingsfrequenz von zwei Einheiten pro Woche, eine Anzahl von 24 – 36 Trainingseinheiten, eine Dauer von 4 – 15 Minuten pro Einheit sowie eine wöchentliche Gesamttrainingszeit von 31 – 60 Minuten den größten Einfluss auf die Gleichgewichtsleistung von Jugendlichen hatten. Die zusätzlich durchgeführte Metaregression zeigte, dass keine der untersuchten Trainingsvariablen ($R^2 = 0\%$) die leistungssteigernden Effekte des Gleichgewichtstrainings vorhersagen konnte.

In Bezug auf die Daten der ersten Querschnittsstudie ergab die statistische Analyse, dass ein gradueller Anstieg des Schwierigkeitsgrades der Gleichgewichtsaufgabe zu einem Anstieg der posturalen Schwankungen ($p < 0,001$; $d = 6,36$), höherer Aktivität der Beinmuskulatur ($p < 0,001$; $2,19 < d < 4,88$) sowie höherer Koaktivität der Beinmuskulatur ($p < 0,001$; $1,32 < d < 1,41$). Während der Ausführung der Gleichgewichtsaufgabe mit ansteigendem Schwierigkeitsgrad war die Zunahme der posturalen Schwankungen und der Aktivität der Beinmuskulatur primär zwischen niedrigen und hohen Schwierigkeitsgraden zu beobachten. Die Ergebnisse der zweiten Querschnittsstudie zeigten, dass ein gradueller Anstieg des Schwierigkeitsgrades der Gleichgewichtsaufgabe einen frequenzspezifischen Anstieg bzw. Abfall der kortikalen Aktivität ($p < 0,005$; $0,92 < d < 1,80$) in verschiedenen Hirnarealen zur Folge hat. Auf kortikaler Ebene nahm die Aktivität innerhalb der Thetafrequenz in frontalen und zentralen Hirnarealen mit höheren posturalen Anforderungen zu. Die Aktivität in der Alpha-2-Frequenz nahm hingegen gleichzeitig in parietalen Hirnarealen ab.

Fazit: Gleichgewichtstraining ist eine effektive Methode, um die statische und dynamische Gleichgewichtsleistung und somit die postural Kontrolle von Kindern und Jugendlichen zu verbessern. Dennoch konnte keine der untersuchten Trainingsvariablen (d.h., Dauer, Frequenz, Umfang) die trainingsinduzierten Effekte auf die Gleichgewichtsleistung erklären. Die im Rahmen der Querschnittsuntersuchungen beobachteten Anstieg der posturalen Schwankung sowie der Aktivität und Koaktivität der Beinmuskulatur waren auf den Anstieg des Schwierigkeitsgrades der Gleichgewichtsaufgabe zurückzuführen. Gleichzeitig deuten die auf bestimmte Hirnareale begrenzte frequenzspezifischen Anstiege bzw. Abfälle der kortikalen Aktivität die Beteiligung frontoparietaler Areale bei regulatorischen Prozessen der posturalen Kontrolle bei ansteigender Aufgabenschwierigkeit an. Somit lässt sich konstatieren, dass die Steigerung des Schwierigkeitsgrades einer Gleichgewichtsaufgabe mittels Verkleinerung der Unterstützungsfläche leicht umgesetzt werden kann. Da es bis dato keine valide Methode zur Erfassung der Intensität eines Gleichgewichtstrainings gibt, erscheint die Steigerung der Aufgabenschwierigkeit als praktische Alternative, um Progression in Gleichgewichtstrainingsinterventionen bei gesunden Jugendlichen quantifizieren und implementierern zu können.

Schlagwörter: Jugendliche, Gleichgewicht, postural Schwankung, Muskelaktivität, kortikale Aktivität, Gleichgewichtstraining, Aufgabenschwierigkeit

List of figures and tables

Abbreviations

BF	m. biceps femoris
BoS	base of support
BT	balance training
BTD	balance task difficulty
CAI	coactivation index
CoM	center of mass
CoP	center of pressure
EEG	electroencephalography
EMG	electromyography
GM	m. gastrocnemius medialis
IC	independent component
MEP	motor evoked potential
PEDro	Physiotherapy Evidence Database
PHV	peak height velocity
PL	m. peroneus longus
rmANOVA	repeated measures analysis of variance
SICI	short interval intracortical inhibition
SMD	standardized mean difference
SMD_{wm}	weighted mean standardized mean difference
TA	m. tibialis anterior
TMS	transcranial magnet stimulation
VM	m. vastus medialis

1. General introduction

Postural control emerges from the complex interaction of the musculoskeletal and neural systems responsible for controlling the proper alignment of body segments and keeping the body over the base of support (BoS) to maintain and recover balance (Shumway-Cook & Woollacott, 2012). Its development is crucial for the acquisition of complex motor skills during childhood to successfully cope with the requirements of daily tasks and during sports activities across the life span. Even though postural control develops from early to middle childhood, adolescence, and finally to adulthood through processes of growth and maturation (Mickle et al., 2011; Nolan et al., 2005; Shumway-Cook & Woollacott, 1985; Steindl et al., 2006), it is strongly affected by the individual’s level of activity. Evidence from cross-sectional studies (Asseman et al., 2008; Behm et al., 2005; Paillard et al., 2006) has suggested a relationship between postural control, physical activity, and sports expertise. Moreover, two review articles (Hrysomallis, 2011; Kiers et al., 2013) addressing this relationship have found balance performance to be associated with physical activity and athletic performance increases such as vertical jumping height or movement speed. Therefore, it seems reasonable to argue that high-level sports performance partly depends on high-level postural control in sports-specific situations. Given that force output decreases by about 30% under unstable conditions (Behm & Colado, 2012) due to center of mass (CoM) misalignment relative to the BoS (Behm et al., 2010a, 2010b), superior balance performance could increase measures of physical fitness (e.g., vertical jumping, change-of-direction tasks) in these conditions as a proper alignment of the CoM in relation to the BoS may result in more effective force transduction (Anderson & Behm, 2005). Moreover, when considering sports incorporating highly dynamic situations (e.g. soccer, handball, basketball) where the proper dynamic alignment of CoM relative to BoS has to be realized in a split second and is decisive for successful performance (Anderson & Behm, 2005; Behm et al., 2011), superior postural control potentially tips the scale.

A well-established method to improve postural control and, consequently, balance performance is balance training (BT). There is compelling evidence indicating the effectiveness of BT on balance performance and injury prevention (Brachman et al., 2017; Lesinski et al., 2015a, 2015b; Roessler et al., 2014). Besides, it has been shown that BT can improve sports-related performance (i.e., shuttle run) in young adults (Yaggie & Campbell, 2006) and sports-specific performance (e.g., passing and shooting) in youth soccer players (Ce et al., 2018). Thus, BT has the potential to antagonize performance impairments in highly dynamic (sports-related) situations. On the contrary, if postural control is neglected, injury risk may increase and the individual may not exhaust immanent adaptive capacities, for instance in sports-related tasks. The beneficial effects of BT on balance performance have been studied in youth and adult populations (Granacher et al., 2006; Heitkamp et al., 2001; Verhagen et al., 2005; Yaggie & Campbell, 2006). The presence of the positive effects were substantiated with meta-analytical evidence only in healthy young (Lesinski et al., 2015a) and older adults (Lesinski et al., 2015b), as well as compared to other training methods (i.e., plyometric, resistance training) (Zech et al., 2010). However, similar systematic and comprehensive approaches for the youth population are missing. Consequently, it is necessary to fill this gap in the literature and complement the body of knowledge regarding the effectiveness of BT on balance performance in youth.

Generally, training interventions (e.g., balance, resistance, endurance training) are prescribed using the following training modalities: training period, frequency, volume and intensity. To optimize the training-induced effects, these training modalities must be optimally combined and dosed. For training methods aiming to improve energetically driven qualities (i.e., muscle strength, aerobic endurance) such as resistance and endurance training, all four training modalities can be easily quantified and manipulated. More specifically, one-repetition maximum, heart rate reserve, or rating of perceived exertion scales (i.e., BORG scales) are main intensity indicatives in resistance and aerobic training, respectively. However, it is not established yet how to quantify intensity in BT. In contrast to muscle strength and endurance, postural control is essentially neuronally driven as adaptive mechanisms following BT are mainly located on the spinal (e.g., increased presynaptic inhibition) (Taube et al., 2008; Taube, Kullmann et al., 2007) and supraspinal levels (e.g., decreased cortical excitability) (Taube et al., 2008; Taube, Gruber et al., 2007). Even though information on BT intensity in interventional studies is missing (Farlie et al., 2018; Lesinski et al., 2015a, 2015b) and cannot be assessed due to the absence of psychometrically valid measures (Farlie et al., 2013), meta-regressional evidence (Farlie et al., 2018) suggests that there must be another training modality besides training period, frequency, and volume that is primarily responsible for effects on balance performance following BT. A potential alternative to BT intensity yet to be considered enabling the control of training progression and BT effectiveness could be balance task difficulty (BTD).

BTD can be easily increased through the manipulation of various environmental conditions that incorporate the surface stability, the individuals’ vision, the training device used, and the size of the BoS. Several studies in adults have indicated that increased difficulty of a continuous balance task induced by manipulating these environmental conditions affects balance performance (Donath et al., 2016; Muehlbauer et al., 2012) and neurophysiological outcomes, such as lower limb muscle activity (Cimadoro et al., 2013; Dohm-Acker et al., 2008; Donath et al., 2016; Licen et al., 2019; Muehlbauer et al., 2014), muscle coactivation (Donath et al., 2016), and cortical activity (Edwards et al., 2018; Hülsdünker, Mierau, Neeb et al., 2015; Hülsdünker, Mierau & Strüder, 2015). For example, Muehlbauer et al. (2012) examined the effects of manipulating BoS, surface stability, and vision on balance performance in young adults aged 22 years. Based on their findings, the authors concluded that balance performance decreases were the result of increasing task difficulty induced by the limitation of sensory inputs (e.g., occlusion of vision) and reduction of the BoS. In another study, Muehlbauer et al. (2014) showed that increasing task difficulty through limiting sensory information resulted in decreased balance performance and increased lower limb muscle activity in single-leg stance in young adults aged 23 years. Similar results were reported by Cimadoro (2013), who found increased lower limb muscle activity when increasing task difficulty using training devices (i.e., balance boards) with different sizes of BoS. Moreover, Hülsdünker, Mierau Neeb et al. (2015) and Hüldünker, Mierau & Strüder (2015) examined the effects of modulating BoS, surface stability, and vision while performing continuous balance tasks on cortical activity in young adults aged 25 years. The same authors reported frequency-specific changes in cortical activity at fronto-central and centro-parietal electrodes of the brain measured via electroencephalography (EEG) while task difficulty increased.

Of note, all the above-cited studies included adult populations, highlighting a void in the literature related to youth individuals. Additionally, the effects of manipulating factors such as BoS, surface stability, vision, and training device were combined to increase task demands. It therefore remains unclear to what extent these factors separately contribute to BTD. Moreover, there is ample evidence that balance follows the principle of training specificity (Behm & Sale, 1993) implying that improvement of specific tasks requires task-specific training (Freyler et al., 2016; Giboin et al., 2015; Kiss et al., 2018; Kümmel et al., 2016). According to this, BTD must be adapted using a standardized BT device mimicking the specific demands of a trained task. The use of varying BT devices (e.g. balance board, pad, spinning top, etc.) may cause bias, and thus the research question on the influence of increasing BTD cannot be answered. As such, it is necessary to elucidate how gradual changes of the BoS using a single BT device affect balance performance and neurophysiological outcomes while all other environmental conditions are kept constant. Consequently, modulations in balance performance, muscle activity, muscle coactivation, and cortical activity can solely be attributed to the systematic manipulation of BoS. The findings from adults on balance performance and neurophysiological outcomes cannot be generalized to youth due to reasons related to ongoing processes of growth and maturation of the postural control system. However, knowledge of the underlying biomechanical (i.e., postural sway) and neurophysiological correlates (i.e., lower limb muscle activity, muscle coactivation, cortical activity) of postural control in youth is crucial. It can help successfully design and adopt BT regimens for the general youth population to achieve high effectiveness.

Taken together, previous systematic reviews and meta-analyses have examined the effects of BT on balance performance in adult populations and established dose-response relationships for respective training modalities in BT (Lesinski et al., 2015a, 2015b). However, these systematic analyses were not able to identify one key training modality responsible for its effectiveness in enhancing balance performance leading to the assumption that a training modality could still be missing. Furthermore, the available studies on the effects of an increasing BTD on balance performance and neurophysiological outcomes in adults have applied various environmental conditions simultaneously to increase task difficulty (Cimadoro et al., 2013; Donath et al., 2016; Edwards et al., 2018; Hülsdünker, Mierau, Neeb et al., 2015; Muehlbauer et al., 2012). Therefore, contributions of a single environmental condition to BTD and its effect on balance performance and neurophysiological outcomes cannot be clearly identified for either adults or youth. Therefore, the present cumulative thesis comprises two parts. The first part consists of a systematic review and meta-analysis on the effects of BT on measures of balance performance in youth (Gebel et al., 2018). The second part involves two cross-sectional studies. The first addresses the effects of BTD on balance performance, muscle activity, and muscle coactivation (Gebel et al., 2019), and the second addresses the effects of BTD on balance performance and cortical activity in adolescents (Gebel et al., 2020) to further understand the underlying neurophysiological correlates of postural control.

2. Literature review

This literature review provides information on the function and development of postural control in youth. It furthermore elaborates on the important role of BT in promoting postural control in youth and gives an overview of training-induced improvements of balance performance and other measures of physical performance. In addition, the present chapter outlines the results of previous research regarding potential underlying neurophysiological mechanisms responsible for BT-specific adaptions and, finally, summarizes the modulating effects of BTD on balance performance, muscle activity, and cortical activity.

2.1. Postural control in youth

Postural control represents the ability to properly align the body segments and the body's CoM in relationship to the BoS for the purpose of orientation and stability, respectively. It relies on the intricate interaction between the musculoskeletal and neural systems, allowing the successful performance of complex body movements under steady and constantly changing environmental conditions (e.g., predictable/unpredictable, stable/unstable, unperturbed/perturbed, static/dynamic) (Shumway-Cook & Woollacott, 2012). This is realized through the continuous integration of sensory information from the visual, somatosensory, and vestibular systems within the central nervous system. Whereas postural control under simple environmental conditions (e.g., upright unperturbed stance) is rather automatic and dominated by the somatosensory system, all sensory inputs (i.e., visual, somatosensory, vestibular) will be reweighted and voluntary control will increase under complex conditions (e.g., unpredictable postural perturbations in bipedal stance) according to the specific situational demands (Taube & Gollhofer, 2011). However, as infants are unable to sit, stand, or walk right after birth, postural control develops from early childhood throughout youth at the same time as physiological systems (e.g., nervous, muscular, skeletal system) mature. Consequently, the development of postural control is closely linked to the maturation of the physiological systems affecting the timing and rate of development of postural control. Furthermore, it seems to proceed in the direction of the cephalocaudal axis, as it comprises the following milestones on the motor level: crawling (2 months), sitting (6 – 7 months), creeping (8 – 10 months), pull-to-stand (9 – 10 months), independent stance (12 – 13 months), and independent walking (14 – 18 months) (Shumway-Cook & Woollacott, 2012). The emergence of these motor milestones is accompanied by other crucial developmental changes, including changes in motor components (e.g., body morphology, postural synergies) and refinements within the sensory systems (e.g., predominance of sensory systems), contributing to developmental improvements of postural control as shown by Shumway-Cook and Woollacott (1985). In their fundamental research, they examined postural response synergies, dependency on sensory inputs, and the capacity to resolve inter-sensory conflict in children aged 15 – 31 months, 4 – 6 years, and 7 – 10 years. By comparing postural sway, electromyographic activity of the leg muscles, and joint kinematics during translational and rotational postural perturbations between the three age groups, the authors found significant differences in children's postural response synergies and their characteristics. Response synergies in children aged 6 years and younger were direction-specific but had high variability in their organization including activation pattern (e.g., onset, timing, force relationship between distal and proximal muscle synergists), large amplitudes, and long response duration compared to older children (7 – 10 years) who used adult-like patterns. Moreover, the youngest age groups showed diminished stability under altered sensory conditions (i.e., sway-referenced stance, eyes opened/closed), particularly when sensory inputs were incongruent. Shumway-Cook and Woollacott (1985) suggested that the age between 4 and 6 years represents a stage of transition to an adult form of postural organization. Around this age, dependency on sensory inputs for postural control seems to shift from primarily visual to a combination of somatosensory and visual inputs accompanied by refinements of the organization of postural response strategies. They further proposed the occurrence of mature postural control in children aged 7 – 10 years (Shumway-Cook & Woollacott, 1985). More recent studies (Ferber-Viart et al., 2007; Sinno et al., 2020; Steindl et al., 2006) contrasted the hypothesis of Shumway-Cook and Woollacottt (1985) by examining the development of sensory organization in children and adolescents compared to adults utilizing the Sensory Organization Test (SOT) (Nashner et al., 1982). In general, these studies indicated that adult-like postural performance under sensory-conflicting conditions constitutes later during adolescence. More precisely, Ferber-Viart et al. (2007) reported lower test scores (i.e., equilibrium score) in 12 – 14-year-olds than in young adults in all sensory-conflicting conditions of the SOT. Thus, the development of sensory organization seems not to be completed before reaching the age of 15. Findings from Steindl et al. (2006) and Sinno et al. (2020) support this assumption. Both research groups examined different age groups of children and adolescents ranging from 3 years to 17 years by means of the SOT. Compared to the performance of young adults, sensory integration under altered sensory conditions in an adult-like fashion appeared between the ages of 15 and 16 years (Steindl et al., 2006) and 15 and 17 years (Sinno et al., 2020), respectively. These findings suggest that intersensory conflict situations can be resolved in adolescents between the age of 15 and 17 and that the three sensory systems (i.e., somatosensory, visual, vestibular) responsible for postural control mature around that age.

In the past, postural control and its relevant processes of sensory integration were thought to originate from lower levels of the central nervous system. These circuits include structures such as the spinal cord, brain stem, cerebellum, and basal ganglia. However, there is ample evidence from neuroimaging (e.g., functional magnet resonance tomography), magnetoencephalography, functional near-infrared spectroscopy, and EEG studies in adults showing that several cortical areas are also heavily involved in postural control (Jacobs & Horak, 2007; Taube et al., 2008; Wittenberg et al., 2017). Findings from recent EEG studies (Solis-Escalante et al., 2019; Varghese et al., 2019) further suggested the existence of a cortical network contributing to postural control. For instance, Solis-Escalante et al. (2019) reported immediate multifocal power increases within the delta (1 – 3 Hz), theta (4 – 7 Hz), alpha (8 – 12 Hz), beta (13 – 24 Hz), and gamma (30 – 50 Hz) frequency bands after sudden postural perturbation in an upright stance. In addition, Varghese et al. (2019) described finding that cortical functional connectivity rearranged widely across the scalp in temporal association with reactive balance control in the delta, theta, alpha, and beta frequency bands. In contrast, increasing instability during continuous balance tasks resulted in a more restricted cortical activation primarily characterized by increases in fronto-central theta band power and decreases in centro-parietal alpha band power (Edwards et al., 2018; Hülsdünker, Mierau, Neeb et al., 2015; Hülsdünker, Mierau & Strüder, 2015). These frequency and area-specific changes in cortical activity seem to reflect increased posture-related error detection processes and sensory and movement-related information processing, respectively. However, as the adolescents' brain undergoes a continuous process of maturation, reconstruction, and consolidation including the frontal and parietal lobe involved in movement planning and control, attentional processes, and sensory information processing up until the age of 24 (Arain et al., 2013), cortical activity patterns during posturally challenging situations found in adults might not be reflected in the adolescents brain. Moreover, knowledge regarding the underlying neurophysiological correlates of postural control in healthy youth is lacking. While neuroimaging, magnetoencephalography, and functional near-infrared spectroscopy are heavy, stationary, or use an indirect approach (e.g., blood flow oxyganation, hemoglobin concentration) to measure cortical activity, the EEG represents a non-invasive method to directly measure ongoing electrophysiological cortical activity during performance of balance tasks. Thus, EEG-based research investigating frequency and area-specific changes in cortical activity during posturally challenging tasks could help to further understand the postural control system. Further, insights into the underlying neurophysiological correlates would be helpful for systematic approaches to improve postural control in youth, for instance, with BT.

2.2. Balance components and balance training in youth

Postural control can be subdivided into four balance components (i.e., static/dynamic steady-state, reactive, proactive) which are presumed to be highly task-specific as well as independent of each other (Shumway-Cook & Woollacott, 2012). In this context, a few studies (Conner et al., 2019; Granacher & Gollhofer, 2011, 2012; Muehlbauer et al., 2013; Witkowski et al., 2014) analyzed associations between performance measures of static steady-state, dynamic steady-state, and/or reactive balance in healthy untrained children and adolescents. In agreement with Shumway-Cook and Woollacott (2012), they found no associations between different balance components and their performance in either children (Granacher & Gollhofer, 2012; Muehlbauer et al., 2013) or adolescents (Granacher & Gollhofer, 2011; Witkowski et al., 2014). Furthermore, Granacher and Gollhofer (2011, 2012) and Muehlbauer et al. (2013) assumed that different neuromuscular mechanisms may regulate balance components that are direction-specific and characterized by the magnitude of reflex-controlled muscle activation. Findings from a recently published meta-analysis (Kiss et al., 2018) on the associations between the performance of balance components across the life span seem to further substantiate their interdependency and task-specificity. In their analysis, Kiss et al. (2018) reported no associations in children and only marginal associations between the performance of balance components across the life span. Based on these results and considering that different neuromuscular mechanisms may control the four balance components (Granacher & Gollhofer, 2012; Muehlbauer et al., 2013), postural control needs to be trained and tested specifically according to the required balance component. When more than one balance component is involved in successful (balance) task performance, this implicates complementary testing and training of balance. Such structured exercise sequences aiming to improve postural control/balance have been referred to as “balance training,” “proprioceptive training,” “sensorimotor training,” “neuromuscular training,” (Imbiriba et al., 2020; Taube et al., 2008) or “functional training” (Imbiriba et al., 2020) . Since the term “balance training” describes the intended aim of the training (i.e., improving balance) without disregarding the involvement of specific control systems and biological structures, Taube et al. (2008) proposed it as the most appropriate term. In this context, Imbiriba et al. (2020) identified “balance training” as the most consistently used term over the past decades in the literature to characterize interventions enhancing balance performance. To maintain consistency throughout the present doctoral thesis, these training regimens will be referred to as “balance training.”

When conducting BT in youth populations, reardless of whether integrated in other training regimens or applied seperately, maturational status of the youth individuals has to be considered. The process of biological maturation occurs in all physiological systems (e.g., nervous, muscular, skeletal systems) and implicates many changes within the systems. Having in mind that the biological maturation of these systems, including the postural control system and involved sensory systems, develop on different time scales and in a non-linear manner during youth (Kakebeeke et al., 2018; Largo et al., 2003; Lloyd et al., 2016; Quatman-Yates et al., 2012; Shumway-Cook & Woollacott, 1985; Steindl et al., 2006), BT matched to the specific demands faced in youth is essential. Moreover, processes of biological maturation in youth, especially the growth spurt during adolescence, seem to negatively affect postural control (John et al., 2019; Wachholz et al., 2020). For instance, Wachholz et al. (2020) examined differences in postural movement components via principle component analysis during tandem stance (eyes opened/closed) in male adolescents with a mean age of 13.2 years compared to adults. The authors found looser postural movement control in adolescent than in adults indicating impaired postural control and the potential presence of a growth spurt-related phenomenon called adolescent awkwardness (Wachholz et al., 2020). Additionally, John et al. (2019) investigated whether static and dynamic postural control is altered through processes of growth and maturation in male youth soccer players. Maturational status was determined via years from peak height velocity (PHV). Pre-PHV boys displayed better performance on tests assessing static (Balance Error Scoring System) and dynamic postural control (Y-Balance Test) than their older peers in the peri-PHV and post-PHV groups. Consequently, it is not surprising that the age at PHV, a phase of many changes within the physiological systems, coincides with increased injury risk in sports (Bult et al., 2018; Plisky et al., 2006; van der Sluis et al., 2014). This again underpins the importance of BT in youth not only to help develop and improve postural control but also to counteract potential growth and maturation-related impairments in postural control and balance-related physical performance.

2.2.1 Effects of balance training on balance performance and other measures of physical performance

Since the primary purpose of BT is to improve postural control, it is not surprising that BT is frequently applied in various youth populations. Further, in numerous studies the beneficial effects of BT have been shown in children and adolescents, resulting in improvements in component-specific balance performance. For instance, Kayapinar (2010, 2011) found large-sized improvements in static (i.e., duration in unipedal stance on a balance beam) (Kayapinar, 2011) and dynamic (i.e., duration in horizontal on a stabilometer) (Kayapinar, 2010) balance performance in children aged 5-7 years after 12 weeks of BT compared to a control group. The BT protocol was applied three times a week for a duration of 25 minutes per session and incorporated basic postural movements as well as a variety of children's games. Moreover, Schedler et al. (2020) recently examined the impact of a 5-week BT intervention on static and dynamic steady-state balance in children and adolescents aged 7-8 and 14-15 years, respectively. When compared to age-matched peers, children showed significant large-sized improvements in measures of static (i.e., postural sway) and dynamic steady-state balance (i.e., gait speed), whereas large-sized improvements were limited to dynamic steady-state balance in adolescents. Notably, the authors observed no improvements in reactive and proactive balance performance in both age groups. Additionally, significant low-to-medium-sized improvements were reported for measures of static (i.e., timed unipedal balance test with eyes closed) and dynamic balance performance (i.e., timed unipedal balance test on a foam pad) after six weeks of BT in adolescent high-school students, with a mean age of 16 versus active controls of the same age (Emery et al., 2005). Apart from the performance-enhancing effects on static and dynamic balance, Emery et al. (2005) provided some evidence for an injury-preventive effect of BT, as the relative risk of sustaining an injury was lower in the intervention group over six months. Overall, these studies provide evidence for a high effectiveness of BT in untrained (young) children and adolescents. Consequently, one could argue that the observed effects are dependent on the available adaptive reserve, which might be higher in untrained than in trained children and adolescents. In fact, the effectiveness of BT on measures of static and dynamic postural control seems to be unaffected by the training status as studies in trained children and adolescents competing in posturally demanding sports such as gymnastics, soccer, and figure skating have indicated. For instance, Dobrijević et al. (2016) observed significant moderate performance increases in static postural control (i.e., duration in unipedal stance on a balance beam) following four weeks of BT in female gymnasts aged 7 and 8 compared to an active control. Furthermore, Gioftsidou et al. (2006) examined the effects of a 12-week BT program and its timing on dynamic postural control in adolescent male elite soccer players aged 16 years. Compared to an active control group, 20 minutes of BT performed three times a week resulted in significant large-sized improvements in dynamic postural control. Interestingly, the timing of training seemed to have no influence on the effectiveness as BT was equally effective performed as warm-up or cool-down. Finally, Kovacs et al. (2004) conducted a 4-weeks BT intervention in male and female figure skaters with a mean age of 18 years and reported significant small-sized effects on static and dynamic postural control compared to an active control.

However, apart from the performance-enhancing effects on balance components, BT has been shown to be effective in improving physical qualities like agility, power, speed, and strength as well as sports-related performance (Bruhn et al., 2004; Gruber & Gollhofer, 2004; Gruber, Gruber et al., 2007; Heitkamp et al., 2001; Yaggie & Campbell, 2006). These potential transfer effects were first studied in adults. For example, Heitkamp et al. (2001) examined the effects of six weeks of balance compared to strength training on maximal isometric knee extensor and flexor force as well as static balance performance in healthy young adults. The authors reported significant gains in maximal isometric knee extensor and flexor force in both legs and improvements in static balance performance for both training groups. Notably, increases in muscular strength of the BT group were similar to those of the strength-training group, whereas muscular imbalances between legs were only eliminated in the BT group. Furthermore, 4 weeks of BT in young adults significantly increased the rate of force development during maximal isometric leg extensions and electromyographic activity of the knee extensor muscle at contraction onset (Gruber & Gollhofer, 2004). Based on these findings, the authors assumed that BT was potentially beneficial for muscle actions with initially high contraction speeds. Similar findings of an increased rate of force development during maximal isometric contractions following 4-weeks of BT were reported by the same research group for the ankle plantar flexors (Gruber, Gruber et al., 2007). Additionally, electromyographic median frequency of the gastrocnemius medialis (GM) and tibialis anterior (TA) as well as contractile impulses of all recorded muscles (GM, TA, soleus) increased after BT but were less pronounced than in the control group which performed ballistic strength training. Interestingly, mean amplitude voltage of the ankle flexors in the BT group remained unchanged whereas it increased in the strength-training group. Both Gruber und Gollhofer (2004) and Gruber, Gruber et al. (2007) assumed that specific neural adaptions (see section 2.2.3) were responsible for BT-induced effects on performance and that the underlying neural mechanisms were different from those in strength training.

Likewise, studies in children and adolescents (Granacher et al., 2010; Mahmoud, 2011; Taube, Kullmann et al., 2007) provide evidence that the effects on physical and sports-related performance following BT observed in adults are valid for the youth population as well. Mahmoud (2011), for instance, investigated in a controlled trial the effects of BT on measures of physical and sports-related performance in youth basketball players with a mean age of 11 years. After 8 weeks of training, the BT group improved significantly in all measures of physical (e.g., timed single-leg stance eyes opened/closed, vertical jump height) and sports-related (e.g., timed dribbling through a parkour, dribbling and passing on targets) performance except for the trunk bending test compared to an active control (Mahmoud, 2011). Moreover, Ce et al. (2018) examined the effects of a 12-week BT protocol on static/dynamic postural control and on sports-specific skills (i.e., shooting, passing) in 10-year old soccer players in contrast to an active control group. Results indicated larger improvements in static (e.g., bipedal stance eyes closed) and dynamic postural control (e.g., single-leg stance on an unstable surface) for the BT group. Additionally, performance increases in both the passing and shooting tests (e.g., passing and shooting accuracy) were more pronounced after BT. In another study (Taube, Kullmann et al., 2007), adolescent elite ski jumpers aged on average 15 years performed either a 6-week balance or strength training intervention to investigate its impact on muscular strength and vertical jumping performance. Taube et al. (2006) reported significant performance increases for countermovement, squat, and drop jumps following both training methods, whereas maximal isometric muscle strength was only enhanced after strength training. Finally, Granacher et al. (2010) compared the effects of four weeks of BT on postural sway, vertical jumping height, and leg extensor strength in adolescent high school students aged 19 years. When contrasted with an active control group, BT resulted in significant improvements in postural sway, vertical jumping height, and leg extensor strength. Taken together, the available literature provides ample evidence that BT improves balance performance as well as physical and sports-related performance in children and adolescents. In contrast to young (Lesinski et al., 2015a) and old adults (Farlie et al., 2018; Lesinski et al., 2015b), these BT-induced performance improvements particularly regarding balance performance have not yet been systematically and statistically aggregated.

2.2.2 Training specificity

Almost three decades ago, Behm und Sale (1993) introduced the concept of training specificity for resistance training. This stated that training content has to closely mimic the task to be tested in order to achieve the greatest effectiveness. Considering that balance components are independent and task-specific, component specific BT should only improve performance in trained components with no transfer to performance of the untrained components. Consequently, it is not surprising that recent research (Freyler et al., 2016; Giboin et al., 2015, 2018; Giboin et al., 2019; Kümmel et al., 2016; Nagy et al., 2018; Volery et al., 2017; Wälchli et al., 2017; Wälchli et al., 2018) on the specificity of BT could provide evidence for the validity of this concept in BT. For instance, Giboin et al. (2015) examined in two intervention groups contrasted with a passive control how a 2-weeks balance task-specific training affected the performance of the trained and an untrained balance task in young adults. After six sessions, both intervention groups significantly increased performance on the trained balance task, with no transfer to performance on the untrained task. In another study, Giboin et al. (2019) investigated the effects of 6 weeks of varied BT in contrast to plyometric training and passive control on two untrained balance tasks and peak power during counter movement jump in healthy young adults. The authors reported that neither 6 weeks of varied balance training nor the same amount of plyometric training improved performance of an untrained balance task. Moreover, Freyler et al. (2016) contrasted the effects of a 4-week traditional BT with a reactive BT on static and reactive balance performance. The results indicated increases in static and reactive balance performance irrespective of the training received. However, improvements were augmented when training and testing coincided the most (Freyler et al., 2016). These findings were further substantiated in a meta-analysis by Kümmel et al. (2015) who found moderate-to-large performance improvements on trained tasks after BT but no transfer effects on an untrained balance task, indicating that BT follows the specificity principle.

Nevertheless, whereas these findings were primarily based on studies in adults, there is some evidence that BT protocols have to be designed to meet the specific demands of children and adolescents respective of their age and maturity. For example, Granacher et al. reported non-significant small-to-medium-sized improvements on dynamic balance performance after a 4-week traditional BT (i.e., balance exercises on balance boards, soft mats, ankle disks) integrated into regular physical education classes (45 minutes per session, three times a week) in prepubertal children aged 6-7 years when compared to an active control group. The authors concluded that immaturity of the postural control system and deficits in attentional focus might be responsible for the indeterminate effects of traditional BT on dynamic balance. On the other hand, traditional balancing exercises using typical training devices might also be less appealing to children. This might cause children to be less involved in and easier to distract from performing training exercises. Therefore, Keller et al. (2014) examined how 4 weeks of ice skating promoted postural control in children (mean age of 13 years) compared to an active control group participating in regular physical education classes. The training sessions included basic ice-skating techniques and skating through parcours, with dual-tasks, different games, and basic techniques of figure skating and ice hockey. Performance in static, reactive, and proactive postural control increased significantly after ice-skating training but not after physical education. The authors concluded that ice-skating could be used as an alternative to traditional BT to improve postural control in youth (Keller et al., 2014). In a more specific study design, Wälchli et al. (2017) investigated the effects of child-oriented BT on balance performance in different age groups compared to age-matched controls. The child-oriented BT comprised various exercises and games (e.g., balance circuit, Parkour, competitive balance games) to promote the intrinsic motivation of the child. When compared to 11-12 and 14-15-year-olds, children aged 6-7 years showed superior improvements in static and dynamic postural control. The authors concluded that a young age is not a limiting factor in improving postural control when age-specific demands are considered in designing training content. Overall, these findings emphasize that training content should be matched to the specific needs of the respective age groups. A variety of exercises and facilitation of intrinsic motivation seem to play an important role in increasing the impact of BT in youth. Further, training exercises should mimic the target activity in accordance with the concept of training specificity to optimize the effectiveness and hence improve performance.

2.2.3 Neurophysiological mechanisms

As already mentioned in section 2.2.1, adaptive processes responsible for increases in balance and other measures of physical performance following BT were assumed to be primarily located on the neural level (Gruber & Gollhofer, 2004; Gruber, Gruber et al., 2007). In their review, Taube et al. (2008) discussed BT-induced neurophysiological adaptions on the spinal and supraspinal levels. Reflex responses initiated on the spinal level serve to counteract fast but not very challenging postural perturbations in order to maintain or regain balance. Muscle spindles register the change in muscular length induced by a sudden perturbation and subsequently release action potentials. Transmitted via Ia-afferents, these action potentials activate the homonymous alpha-motoneuron, which induces a reflex response 40-50ms after the perturbation-induced change in muscle length. Training-induced modulations of spinal reflex responses, for example, depend on the functional relevance of those reflexes for task-specific postural control. Hence, on the one hand, spinal reflex responses are suppressed when they antagonize successful postural control (Taube, Kullmann et al., 2007). On the other hand, spinal reflex responses are augmented when they contribute to task-specific balance performance (Granacher et al., 2006). Additionally, Gruber et al. (2007) reported reduced spinal reflex responses (i.e., H_{max}/M_{max}) at rest after 4 weeks of BT in young adults, assuming that these might represent general adaptions to long-lasting BT. The same research group (Taube, Gruber et al., 2007) tested in another study using transcranial magnet stimulation (TMS) whether these observed training-induced reductions in spinal reflex responses originate from spinal or supraspinal adaptations. Therefore, Taube, Gruber et al. (2007) investigated neural adaptations to short-latency responses (spinal reflex) and long-latency responses (transcortical reflex) of the soleus muscle during postural perturbations in bipedal stance after 4 weeks of BT in young adults. Compared to a control group, results for the BT group indicated training-induced reductions in the ratio between maximal H-reflex amplitudes and maximal direct muscle responses (i.e., H_{max}/M_{max} ratio) (spinal level), reductions in motor-evoked potentials (MEP) (corticospinal level), and reductions in TMS-conditioned H-reflexes (cortical level) during transcortically mediated long-latency responses of the soleus muscle, but not during short-latency responses. The authors suggested increased pre-synaptic inhibition and changes in corticomotoneuron excitability as potential underlying mechanisms for reduced excitability on the spinal (i.e., H_{max}/M_{max} ratio) and cortical levels (i.e., TMS conditioned H-reflex), respectively. Since only stance stability and reductions in TMS-conditioned H-reflexes were correlated, Taube, Gruber et al. (2007) assumed that primarily supraspinal adaptations wer accountable for improving balance performance. Later, Taube et al. (2008) complemented that reduced cortical excitability might also represent a transfer of movement control from cortical to subcortical structures (Figure 1). While previous research (Nandi et al., 2018; Nandi et al., 2019; Papegaaij et al., 2014; Papegaaij et al., 2016; Tokuno et al., 2018) demonstrated increases in corticospinal excitability and decreases in intracortical inhibition with increasing postural challenges, it might be suggested that the cortical inhibitory network adapts as a result of BT. In this context, Mouthon and Taube (2019) recently published a study examining whether balance performance improvements after two weeks of BT are concomitant with changes in SICI. TMS was applied before and after BT to test training-induced changes of SICI in the TA. The authors reported improved postural control accompanied by increased levels of SICI in the TA after 2 weeks of specific BT on a stabilometer and concluded that these findings demonstrated the occurrence of cortical plasticity in general and adaptation of inhibitory circuits in particular following BT (Mouthon & Taube, 2019). Moreover, long-term BT in young adults induced functional (i.e., resting state network connectivity) and structural (i.e., alterations in grey/white matter) brain plasticity suggesting that intrinsic brain activity is of functional relevance for morphological adaptations in the human brain as reported by Taubert et al. (2011).

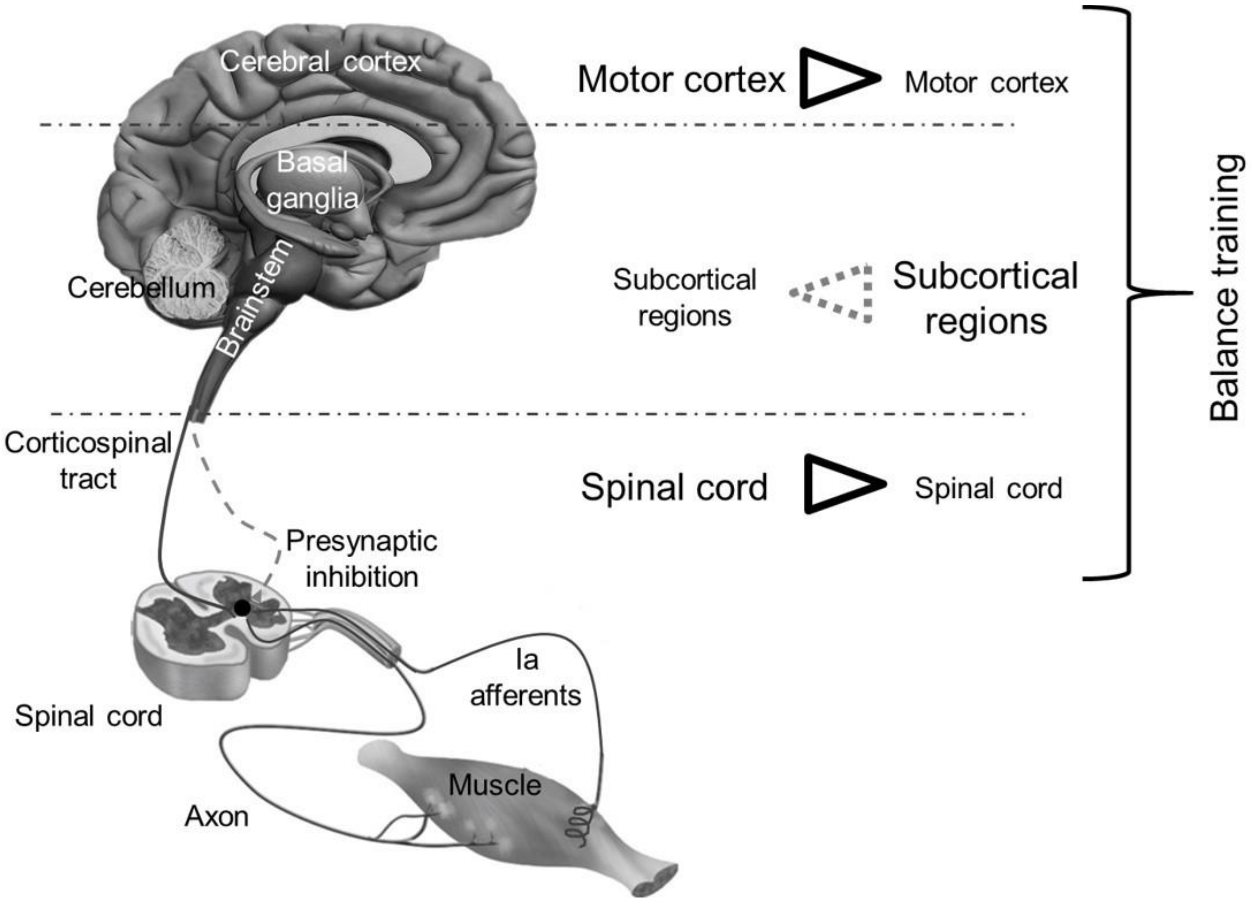

Figure 1 Schematic illustration of the balance training-induced adaptation on the spinal and supraspinal levels (adapted by Taube et al., 2008). While balance training reduces spinal reflex excitability mediated by increases in supraspinal-induced presynaptic inhibition (►) and reduces cortical involvement (►), it is assumed that increased involvement of subcortical structures (◄) is responsible balance training-induced improvements in postural control.

Nevertheless, longitudinal studies that tried to identify the underlying neurophysiological mechanisms of BT were mainly conducted in adults (Gruber, Taube et al., 2007; Mouthon & Taube, 2019; Penzer et al., 2015; Schubert et al., 2008; Taube, Gruber et al., 2007). So far, only a single study has provided evidence for similar training-induced neurophysiological adaptations in youth (Taube, Kullmann et al., 2007). Taube, Kullmann et al. (2007) examined the effects of a 6-week BT on spinal reflex responses by assessing H-reflex amplitudes as well as the H_{max}/M_{max} ratio of the soleus muscle during postural perturbations in 15-year-old nordic ski athletes. In accordance with the findings of Taube, Gruber et al. (2007) in adults, the authors reported decreased H-reflex amplitudes and decreased H_{max}/M_{max} ratios after BT, indicating similar underlying adaptive mechanisms on a spinal level in terms of increased presynaptic inhibition for youth (Taube, Kullmann et al., 2007). Taken together, evidence from the literature suggests that spinal, corticospinal, and cortical excitability after BT is reduced and that supraspinal mechanisms rather than spinal mechanisms seem to account for improvements in postural control (Taube, Gruber et al., 2007; Taube et al., 2008). Further, it can be suggested that these changes are accompanied by training-induced functional and structural brain plasticity (Taubert et al., 2011). However, further research on the adaptive mechanisms of BT in youth is needed. Even though their characteristics and magnitude might be influenced by processes of growth and biological maturation throughout childhood and adolescence, the importance of BT for improving postural control and physical performance has to be emphasized.

2.2.4 Task difficulty as a modulating factor of balance performance and neurophysiological outcomes

Generally, training interventions follow a progressive design to achieve long-term improvements in performance, which are normally implemented through exercise intensity. However, quantification of intensity in BT is an issue. As described in the previous section on how underlying neurophysiological mechanisms of BT are primarily located on the spinal and supraspinal levels, postural control seems to be essentially neuronally driven. This might also explain why there seems to be no psychometrically valid tool available to quantify BT intensity (Farlie et al., 2013). Additionally, the effectiveness of BT could not be predicted by any other training modality (Farlie et al., 2018), indicating that another key modality might exist. Thus, a potential tool to implement progression into BT and control its effectiveness could be an increasing BTD. It can be increased by manipulating the sensory systems (i.e., vestibular, visual, proprioceptive) responsible for postural control and/or modifying biomechanical requirements (e.g., BoS). In practice, this includes the modulation of surface (e.g., firm/foam, stable/unstable), training device (e.g., balance board, wobble board, tilt board), stance (e.g., bipedal, unipedal, step, tandem), or vision (e.g., eyes open/closed). When BTD increases, it typically affects balance performance (Amiridis et al., 2003; Donath et al., 2016; Muehlbauer et al., 2012) and neurophysiological outcomes, such as muscle activity (Amiridis et al., 2003; Dohm-Acker et al., 2008; Donath et al., 2016; Licen et al., 2019; Muehlbauer et al., 2014), muscle coactivation (Donath et al., 2016), corticospinal excitability, and intracortical inhibition (Nandi et al., 2018; Nandi et al., 2019; Papegaaij et al., 2014; Tokuno et al., 2018), as well as cortical activity (Edwards et al., 2018; Hülsdünker, Mierau, Neeb et al., 2015; Hülsdünker, Mierau & Strüder, 2015; Tse et al., 2013). In one of the first studies, Amiridis et al. (2003) examined balance performance and leg muscle activity during bipedal upright stance, tandem Romberg stance, and single-leg stance in young and old adults. Both groups showed increased postural sway and electromyographic leg muscle activity while reducing the BoS, whereas increases were more pronounced in older adults, particularly in the hip muscles. In another study, Muehlbauer et al. (2014) investigated balance performance and lower leg muscle activity in single-leg stance under three different sensory conditions (i.e., eyes open/firm ground; eyes open/foam ground; eyes closed/firm ground) in young adults. The authors reported deteriorated balance performance and increased lower leg muscle activity, with an increase in sensory task difficulty (Muehlbauer et al., 2014). Further, Donath et al. (2016) reported increased ankle muscle coactivation in older adults with increasing BTD compared to young adults. However, both age groups showed difficulty-dependent decreases in balance performance. The authors argued that based on the differences in muscle coactivation with increasing BTD, older adults might change their postural strategy from an ankle to a hip strategy to obtain more stability (Donath et al., 2016). Apart from performance decreases and increased muscular activity/coactivity, corticospinal excitability, intracortical inhibition, and cortical activity are also affected by BTD. In this context, Tokuno et al. (2018) examined whether changes in postural threat were responsible for the alterations in corticospinal excitability and SICI that occur with increasing postural task difficulty. Thirteen adults performed a postural task under three levels of task difficulty and two postural threat conditions. During task performance, TMS was applied to compare MEP and SICI of the ankle muscles between conditions. As MEPs increased and SICI decreased with increasing postural difficulty but not with postural threat, the authors assumed that task difficulty was responsible for the observed neurophysiological changes. Further, EEG research (Edwards et al., 2018; Hülsdünker, Mierau, Neeb et al., 2015; Hülsdünker, Mierau & Strüder, 2015; Tse et al., 2013) indicates cortical involvement as represented by frequency-specific and area-specific activity changes within the brain during the performance of continuous postural tasks with various levels of difficulty. For instance, Hülsdünker, Mierau, Neeb et al. (2015) examined the alterations in cortical activity occurring in young adults while performing a continuous balance task of increasing difficulty (i.e., bi-/unipedal stance on firm/foam surface). The authors reported increased theta frequency band power (4 – 7 Hz) at frontal, fronto-central, and centro-parietal scalp electrodes, with a progression in balance task-difficulty. Area-specific increases in theta band power were interpreted as processes of error detection and monitoring of stability serving postural control (Hülsdünker, Mierau, Neeb et al. 2015). Further, in a similar study design, the same research group (Hülsdünker, Mierau & Strüder et al. 2015) reported that an increase in difficulty during balance task performance resulted in a decrease in alpha-1 (8 – 10 Hz) and alpha-2 frequency (11 – 13 Hz) band power at centro-parietal scalp electrodes. The authors argued that a decrease in alpha band power in the centro-parietal areas of the brain might reflect higher levels of information processing (alpha-1), particularly sensory information processing (alpha-2) (Hülsdünker, Mierau & Strüder et al. 2015). In conclusion, previous cross-sectional studies demonstrated the effects of an increase in task difficulty during a continuous balance task on balance performance and several neurophysiological outcomes. However, these studies did not examine balance performance, muscular activity, and cortical activity in the same study protocol nor were these findings confirmed in a youth population. Furthermore, previous EEG studies investigating cortical activity during balance task performance remained with their frequency analyses on the electrode level but signal processing techniques including independent component analyses provide the opportunity to locate electro-cortical sources within the brain. Thus, future studies should fill these research gaps by addressing these issues.

3. Research objectives and hypotheses

BT is a well-established training method to improve postural control under varying environmental conditions and to increase performance in daily and sport-specific activities. Apart from improving postural control, BT has the potential to counteract growth and maturation-related impairments in postural control and balance-related physical performance that might occur during adolescence. In contrast to adults, the described training-induced effects on balance performance have not yet been comprehensively and systematically assessed in a youth population. Further, as a key training modality is still missing to explain the effectiveness of BT, and psychometrically valid tools for quantifying intensity are absent as well, BTD could be a promising candidate. Previous cross-sectional studies demonstrated the effects of an increase in task difficulty during a continuous balance task on balance performance and several neurophysiological outcomes including muscle activity, muscle coactivation, and cortical activity emphasizing the potential of BTD as a tool to control the effectiveness of BT. However, these studies did not examine balance performance together with these neurophysiological outcomes in the same study protocol, nor are these findings confirmed in a youth population. Therefore, the primary aims of this doctoral thesis are to examine the effects of BT on balance performance in youth and to elucidate the effects of a gradually increasing BTD on balance performance, muscle activity, muscle coactivation, and cortical activity to further understand the underlying neurophysiological correlates of postural control in youth (Figure 2).

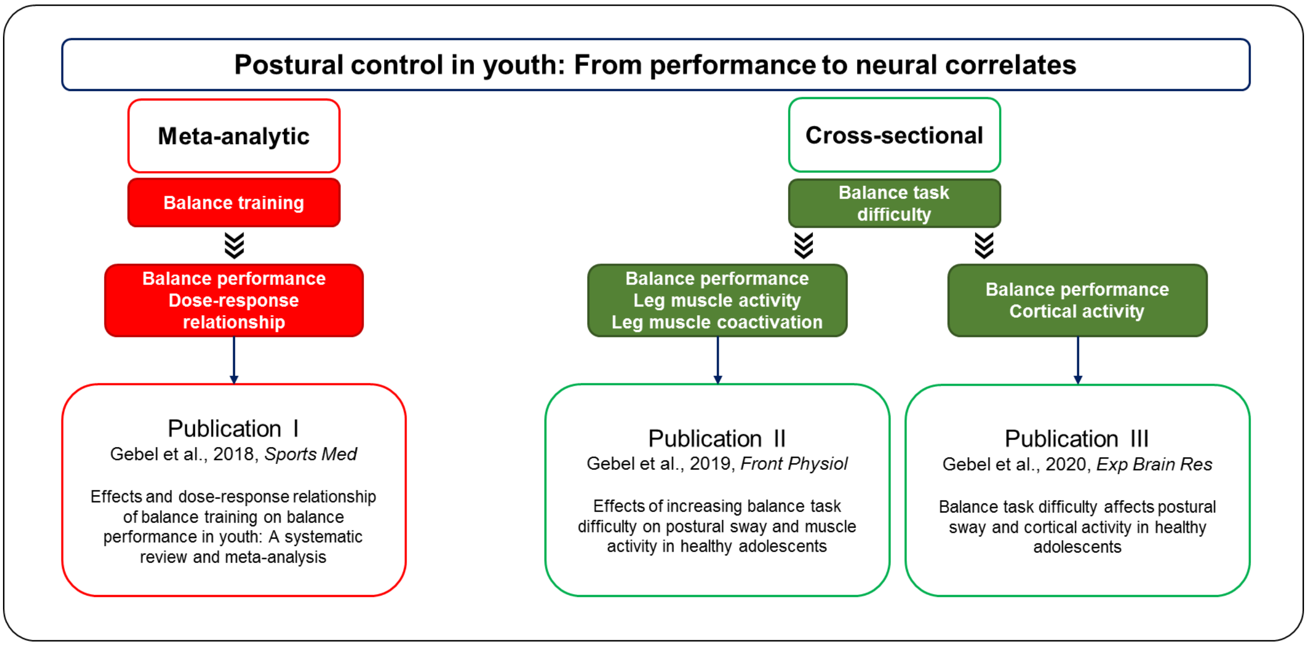

Figure 2 Schematic overview of the aims of the three publications (I, II, III) included in this doctoral thesis

Objective 1

The first objective was to quantify the general effects of BT on static and dynamic balance in youth and to examine the influence of variables like sex, age, training status, setting, and testing method that might moderate training-induced balance outcomes.

Hypothesis 1

Based on the available literature, it was hypothesized that (a) BT is an effective means to improve static (Altınkök, 2015; Granacher et al., 2010) and dynamic balance performance (Altınkök, 2015; Gioftsidou et al., 2006) in youth and that (b) the effectiveness for these measures of balance performance is moderated by the following variables: age, sex, training status, setting, and testing method (Hrysomallis, 2011; Mickle et al., 2011; Steindl et al., 2006).

Objective 2

The second objective was to characterize dose–response relationships for BT modalities (i.e. training period, frequency and volume) that optimize improvements in balance performance in youth.

Hypothesis 2

With reference to previous meta-analyses in young (Lesinski et al., 2015a) and older adults (Lesinski et al., 2015b), it was hypothesized that dose-response relationships for training modalities (i.e. training volume) in youth are comparable to those in adults.

Objective 3

Based on the results of the preceding meta-analyses in youth (Publication I), the research objectives of the two cross-sectional studies (Publications II and III) focused on the impact of increases in BTD in adolescents. Thus, the third objective was to examine the effects of a gradually increasing BTD (i.e., balance board with adjustable BoS) on postural sway in healthy adolescents.

Hypothesis 3

According to the relevant literature, it was hypothesized that postural sway increases with a gradual increase in BTD (Muehlbauer et al., 2012; Cimadoro et al., 2013).

Objective 4

The fourth objective was to examine the effects of a gradually increasing BTD (i.e., balance board with adjustable BoS) on lower limb muscle activity and muscle coactivation in healthy adolescents.

Hypothesis 4

Based on previous studies, it was assumed that lower limb muscle activity (Soderberg et al., 1991; Dohm-Acker et al., 2008; Cimadoro et al., 2013) and coactivation (Donath et al., 2016) increases with a gradual increase in BTD and that the ankle muscles are mainly responsible (Dohm-Acker et al., 2008) for increases in postural sway with increasing task difficulty.

Objective 5

The fifth objective was to examine the effects of a gradual increase in BTD (only by changing the BoS) on frequency band power by means of source space analyses in healthy adolescents.

Hypothesis 5

Based on previous findings from adult studies (Edwards et al. 2018; Hülsdünker, Mierau, Neeb et al. 2015; Hülsdünker, Mierau & Strüder et al. 2015, Sipp et al. 2013; Slobounov et al.

2009), it was hypothesized that a gradual increase in BTD (i.e., only reducing balance boards BoS) results in frequency-specific power changes in frontal, central, and parietal brain areas in adolescents. More precisely, increases in theta (Hülsdünker, Mierau, Neeb et al. 2015; Sipp et al. 2013; Slobounov et al. 2009; Varghese et al. 2014) and decreases in alpha- 2 frequency band (Hülsdünker, Mierau & Strüder et al. 2015) power in fronto-central and centro-parietal brain areas, respectively, were expected with increasing task difficulty.

4. Materials and methods

The following chapter summarizes the participants' characteristics, the experimental procedure, data recording and processing, as well as the statistical analyses. The applied methodological approach in this doctoral thesis was based on the deduced research hypothesis. Detailed information on material and methods can be found in the respective sections of Publications I, II and III.

4.1. Participants

The study sample in Publications II and III consisted of 13 healthy high-school students (3 female/10 male) aged 16-17 years that volunteered to participate in both cross-sectional studies. The sample size was determined by *a priori* power analyses using G*Power (Faul et al., 2009) based on previously reported results regarding the effects of different balance tasks on muscle activity (Cimadoro et al., 2013) and frequency-specific cortical activity (Hülsdünker, Mierau, Neeb et al. 2015). According to the sex-specific equation of Mirwald et al. (2002), age at PHV was calculated to estimate the maturity level of every participant. Participants with any acute injury or any musculoskeletal, neurological, and/or orthopedic disorder of the lower limbs were excluded from this study. Further, all participants and their legal guardians gave their written informed consent before attending the experimental session. The local ethics committee of the University of Potsdam approved the study and its design (application no. 18/2017). The experiment was conducted according to the latest version of the Declaration of Helsinki. Information in detail regarding the participants can be found in the "Methods" section of the respective published manuscripts (see Publications I, II and III).

4.2. Experimental procedures

At the outset of this research project and as basis for the following two cross-sectional studies, a systematic review with meta-analysis on the effects of BT on balance performance in youth

(Publication I) was conducted. To ensure a standardized process, the elaboration of this systematic review with meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis statement guidelines (Moher et al., 2009). Further, the PICOS (participants, interventions, comparators, outcomes, and study design) approach was used to consider the eligibility for including potential studies (Liberati et al., 2009). In terms of study coding, performance measures of static steady-state balance were classified as outcome components for static balance. Measures for proactive balance and tests incorporating quasi-dynamic conditions (e.g., unstable surface) were summarized as dynamic balance. This was done due to the limited number of proactive balance measures and to allow further quantitative analyses.

Regarding both cross-sectional studies, a single-group repeated measures design was used to examine the effects of an increasing BTD on postural sway, lower limb muscle activity, muscle coactivation, and cortical activity (Publications II and III). All participants attended a single lab session starting with a standardized familiarization with the multi-directional BT device and the balance task. The lateral preference inventory (Coren, 1993) was used to determine leg dominance. Subsequently, electrodes for surface electromyography (EMG) were attached to the shank and thigh muscles of the non-dominant leg and the EEG electrode cap was fitted to the participant’s head and prepared. Thereafter, participants performed three sets of six balance tasks. Each set consisted of six levels of BTD. The order of task difficulty levels was randomized for every set. Altogether, participants had to perform 18 trials (3 × level 1 – 6) with a length of 30 s per trial. Postural sway, muscle activity, and cortical activity were recorded while participants executed all balance tasks. Additionally, two separate EEG baseline measurements (3 min) were acquired prior to the first and after the third set. Anthropometrics were tested using a stadiometer (seca 213, seca Gmbh, Hamburg, Germany) and a bioimpedance analysis system (InBody 720, BioSpace, Seoul, South Korea).

4.3. Balance task

The goal of each balance task was to keep the multi-directional balance board (Wobblesmart©, Artzt GmbH, Dornburg, Germany) as still as possible on a horizontal plane and to avoid ground contact with the board edges during all measurements. The participants executed the respective balance tasks in an upright position and without shoes in bipedal stance. Every test trial had a duration of 30 s and started from a standardized position. Participants held on to a handrail in front of them allowing them to start from a quiet stance with the balance board in a horizontal position. Further, participants were asked to perform the balance task in a steady position with their hands akimbo and knees slightly flexed at approximately 30 degrees. To avoid visual distraction, they had to focus their gaze on a fixation cross at eye level on a nearby wall (ca. 3 m distance). An increase in BTD in the respective experiment was established by a mechanically adjustable pivot integrated in the multi-directional balance board. For a detailed description of the balance task, its execution, and the integrated mechanism to increase BTD see the "Methods" section in Publications II and III.

4.4. Data recording and analysis

Both cross-sectional studies (Publications II and III) were conducted in the biomechanical laboratory of the Division of Movement and Training Science at the University of Potsdam (Germany). Measurements comprised the assessment of balance performance, leg muscle activity, muscle coactivation, and cortical activity.

4.4.1. Assessment of methodological study quality

In Publication I, the methodological quality and risk of bias of the studies included in the meta-analysis were assessed by utilizing the Physiotherapy Evidence Database (PEDro) scale (Maher et al., 2003). The scale ranged from 0 to 10 with a score of 0 indicating a very low study quality and a score of 10 indicating a very high study quality. According to Morton (2009), scores of 6 or higher represent a cut-off value for a high study quality. Further, the risk of publication bias was assessed by visual inspection of the respective funnel plots. An asymmetrical distribution of the studies within the funnel plot indicates a publication bias (Egger et al., 1997).

4.4.2. Assessment of postural sway

Postural sway was assessed as a measure of balance performance. Therefore, center of pressure (CoP) displacements were recorded using two pressure-measuring sensor mats (Posturo S2094, novel GmbH, Munich, Germany) placed on the multi-directional balance board. To prevent mats from slipping, they were fixed with double-sided adhesive tape to the balance board. The CoP displacements were recorded with 220 sensors (sensor dimensions: 20 × 20 mm) per mat (mat dimensions: 440 × 220 mm) at a sampling rate of 40 Hz using the Posturo 32 Expert software (version 25.3.6, novel GmbH, Munich, Germany). The absolute path length of the CoP displacements (aggregated displacements in the medio-lateral and anterior-posterior axis) was calculated for each trial within the software and extracted for further analysis. Detailed information on the assessment of postural sway is presented in Publication II.

4.4.3. Assessment of leg muscle activity

The EMG activity of ankle (m. tibialis anterior [TA], m. gastrocnemius medialis [GM], m. peroneus longus [PL]) and thigh muscles (m. vastus lateralis [VL], m. biceps femoris [BF]) was recorded for each trial to assess the leg muscle activity during the execution of the balance task. Synchronization of the EMG signals and postural sway was accomplished by means of a transistor-transistor-logic signal, send via a direct link from the pressure-measuring system (Posturo Sync Box, novel GmbH, Munich, Germany) to the EMG system (TeleMyo 2400R Analog Output Receiver, Noraxon©, Scottsdale, AZ, United States), determining on and offset of every recorded trial. Circular bipolar surface electrodes (Ambu©, type Blue Sensor P-00-S/50, Ag/AgCl,13.2 mm, center-to-center distance 25 mm, Ballerup, Denmark) were positioned on the respective muscle bellies according to the SENIAM guidelines (Hermens et al., 2000). To obtain an electrode impedance below 5 kΩ and achieve a high signal-to-noise ratio, the skin preparation included shaving, slightly roughening, degreasing, and disinfecting. Acquired EMG signals were amplified and recorded telemetrically (TeleMyo 2400 G2, Noraxon©, Scottsdale, AZ, United States) at a sampling rate of 1,500 Hz utilizing the MyoResearch XP Master edition software (version 1.08.17, Noraxon©, Scottsdale, AZ, United States). The same software was used for offline analysis of the EMG-signals. The raw data were digitally band-pass filtered with cut-off frequencies of 10 Hz and 500 Hz, as well as rectified and smoothened by a moving-root-mean-square filter with a time constant of 50 ms. This processing routine was adapted according to Prieske et al. (2014; 2017). For further analyses, the mean amplitude voltage of the non-normalized EMG signal (Halaki & Gi; Luca, 1997) was calculated for the time interval determined by the TTL signal and averaged across all trials within the six levels of task difficulty for each participant and the respective muscle. Due to the multi-directionality of the balance task, it was not possible to distinguish between agonistic and antagonistic muscles. Therefore, mean amplitude voltage for all ankle (TA, GM, PL) and thigh muscles (VL, BF) was aggregated to investigate the effect of an increasing BTD on ankle and thigh muscle activity. Additionally, muscle coactivation in terms of the muscle coactivation index (CAI) for the ankle (TA, GM) and thigh muscles (VL, BF) was calculated to estimate joint stiffness. An increase in joint stiffness supports maintaining stability through a more rigid posture (Benjuya et al., 2004; Hortobágyi & Devita, 2000). In accordance with Donath et al. (2016), the following equation was used for CAI calculation:

$$CAI = \frac{Averaged\ mean\ amplitude\ voltage\ of\ the\ less\ active\ muscle}{Averaged\ mean\ amplitude\ voltage\ of\ the\ more\ active\ muscle}$$

A more detailed description of the assessment of muscle activity and coactivation can be found in Publication II.

4.4.4. Assessment of cortical activity

For quantification of cortical activity during the execution of balance tasks with increasing task difficulty, a mobile EEG system (eego™ sports, Advanced Neuro Technology B.V., Enschede, Netherlands) with 64 Ag/AgCl passive electrodes (Waveguard classic, Advanced Neuro Technology B.V., Enschede, Netherlands) was used. To ensure a high signal-to-noise ratio, electrode impedances were kept below 5 kΩ. A 24-bit amplifier (eego™ sports, EE-225, Advanced Neuro Technology B.V., Enschede, Netherlands) digitized the raw analog signal. The digital signal was recorded with a sampling frequency of 1,024 Hz by means of the eego™ software (ANT Neuro eego™, Version 1.6, Neuro Technology B.V., Enschede, Netherlands).

For offline processing and analysis of the digitized EEG data, an open-source EEG toolbox (EEGLAB 13.5.4b, Delorme & Makeig, 2004) implemented in MATLAB (Mathworks Inc., Natick, MA, USA) was used. Processing of the EEG data followed a similar procedure for each dataset. In a first step, sinusoidal line noise (50 Hz / 100 Hz) was removed through use of the CleanLine plugin (Mullen, 2012) before band-pass filtering the EEG signals with a finite impulse response filter with cut-off frequencies of 3 and 30 Hz. Subsequently, data were down-sampled (256 Hz) and visually inspected, and channels with severe artifact contamination (e.g., electrode movements, non-stereotypical electromyographic activity) were manually removed. After re-referencing, visual inspection of EEG data was repeated to identify and remove single non-stereotypical artifacts from the dataset. In the next step, an adaptive mixture-independent component analysis (Palmer et al., 2011) was applied to the remaining data to identify and extract electro-cortical sources with their spatio-temporal features for each participant in the form of maximally independent and stationary independent components (IC) (Makeig et al., 1996). A four-shell spherical head model implemented in the DIPFIT toolbox (Oostenveld & Oostendorp, 2002) was used to calculate the equivalent dipole models for each IC. For IC classification, a heuristic approach proposed by Onton und Makeig (2006) was used to separate functional activity from stereotypical artifacts. Based on their specific characteristics (i.e., scalp topographic maps, time courses, frequency spectra, and location of the dipole model) ICs were rated as functional and considered for further analysis, whereas ICs with stereotypical artifact patterns (e.g., eye blinks) were dismissed. Remaining ICs were clustered across all participants by means of a k-means algorithm if their single equivalent dipole model revealed 15% or less residual variance from the spherical four-shell head model. ICs with a higher residual variance were not considered for further analysis. Every cluster was composed of ICs located within two standard deviations of the center of the respective cluster. Subsequently, the absolute spectral power for two predefined frequency bands, namely theta (4-7 Hz) and alpha-2 (10-12 Hz), was calculated for each IC and participant from a merged EEG dataset consisting of all three trials per level of task difficulty. Therefore, IC activity was fast Fourier transformed with a spectral resolution of 1 Hz and a 10% Hanning window. To analyze the changes of frequency-specific characteristics as a function of BTD, absolute spectral power for each frequency band was averaged for the participants' IC within the respective cluster.

4.5. Statistical analyses

To examine the effects of BT on static and dynamic balance performance in youth, between-subject standardized mean differences (SMD) were calculated for every included study. For calculation of SMD's, the following formula was used:

$$SMD = \frac{Difference\ in\ mean\ outcome\ between\ groups}{Pooled\ standard\ deviation\ of\ outcome\ among\ participants}$$

Further, respective SMD values were multiplied by the following factor $(1 - \frac{3}{4N_i - 9})$ to adjust for small sample size bias (Deeks & Higgins, 2010). A random-effects meta-analysis model was used to calculate weighted mean SMDs (SMD_{wm}) for respective measures of balance performance. Weighted mean SMDs allow for the comparison of BT effects across many studies on different balance performance outcomes. Moreover, they help to evaluate whether or not differences are of practical concern. The influence of moderator variables and training variables was analyzed by means of subgroup univariate analyses. For this purpose, SMD_{wm} values for specific subgroups were aggregated and weighted subgroup effect sizes were compared using a chi^2 trend test (Deeks & Higgins, 2010). Meta-analysis, subgroup analyses, and respective calculations were conducted using Review Manager V.5.3.5 (The Nordic Cochrane Centre, 2014) and its implemented functions. In addition, dose-response relationships were characterized by utilizing the subgroup with the highest effect size magnitude within each training modality. To elucidate whether a single training modality can predict effectiveness of BT on balance performance in youth, a multivariate random-effects meta-regression was calculated with the software package Comprehensive Meta-analysis version 3.3.70 (Biostat Inc., Englewood, NJ, USA). I^2 and chi^2 statistics were used to assess between-study heterogeneity and rated as recommended by Higgins et al. (2003).

In both cross-sectional studies (Publications II and III), all statistical tests were performed using SPSS (Version 25, IBM, Chicago, IL, United States). The effects of an increasing BTD on postural sway, muscle activity, muscle coactivation, and cortical activity were analyzed by means of a repeated measure analysis of variance (rmANOVA). Model residuals of CoP, EMG, and EEG data were tested for normal distribution via the Shapiro-Wilk test. RmANOVA with the six levels of BTD as repeating factors were calculated for each dependent variable (total CoP displacements, EMG mean amplitude voltage, CAI values, EEG absolute spectral power) separately. When appropriate, degrees of freedom and means of squares were adjusted according to Greenhouse-Geiser correction for non-sphericity. If significant main effects of task difficulty were detected, Bonferroni-corrected post-hoc t-tests were applied to identify differences between single levels of task difficulty within each dependent variable. To examine whether muscle activity (set of muscles and single muscles) can predict total CoP displacements, two forward multiple regression analyses were conducted.

In all publications, the level of significance was set at $p = 0.05$ and effect sizes interpreted according to Cohen (1988), with values ≤ 0.2 as small, values ≤ 0.5 as medium, and ≤ 0.8 as large effects. For a detailed description of statistical methods, see the respective statistics part in the “Methods” section of Publications I, II, and III.

5. Results

The following chapter provides brief information on the main results of Publications I, II, and III included in the present doctoral thesis. Results are presented according to the order of the research objectives.

5.1. Effects of balance training on balance performance in youth

Overall, 17 studies with a total of 833 children and adolescents were identified as eligible and included for quantitative analysis. The methodological quality of these studies was considered as moderate with a median PEDro score of 6 (95% confidence interval 5–6). Quantitative analyses indicated a moderate effect for BT on static balance including 13 studies with 15 intervention groups ($SMD_{wm} = 0.71$; 95% CI 0.42–1.01, $I^2 = 66\%$, $p < 0.001$), and a large effect on dynamic balance including 12 studies with 15 intervention groups ($SMD_{wm} = 1.03$;

95% CI 0.60–1.46, $I^2 = 83\%$, $p < 0.001$) in youth. Further subgroup analysis regarding the effects of moderator variables (i.e., chronological age, sex, training status, setting, testing methods) on overall balance performance which combined all included studies showed no significant effect but revealed a considerable heterogeneity within the subgroups ($I^2 = 86\%$ - 90%). Results on effectiveness of BT on balance performance are described in detail in the results section of Publication I.

5.2. Dose-response relationship of balance training in adolescents

Subgroup-specific analyses in adolescents revealed moderate to large effects of BT on static ($SMD_{wm} = 0.61$; 10 studies) and dynamic balance ($SMD_{wm} = 0.86$; 10 studies) performance. For dose-response relationship analyses, all included adolescent studies were combined to calculate the overall balance, which showed large BT-induced effects ($SMD_{wm} = 0.84$; 13 studies) as well. The findings showed that 12 weeks of BT ($SMD_{wm} = 1.40$; 4 studies), a frequency of two training sessions per week ($SMD_{wm} = 1.29$; 3 studies), a total of 24 – 36 sessions ($SMD_{wm} = 1.58$; 3 studies), durations of 4 – 15 minutes per single session ($SMD_{wm} = 1.03$; 2 studies), and a total duration of 31 -60 minutes of BT per week ($SMD_{wm} = 1.33$; 3 studies) showed the highest effectiveness to improve overall balance performance when considered independently. However, results of the multivariate random-effects meta-regression for the respective training modalities (training period, frequency, total number of training sessions) revealed that none of these modalities ($p = 0.28 – 0.92$) could predict the performance-increasing effects of BT on overall balance in adolescents. Additionally, the proportion of total between-study variance explained by the applied meta-regression model was $R^2 = 0.00$. A detailed presentation of the results of the systematic review with meta-analysis (Publication I) can be found in the respective results section.

5.3. Effects of balance task difficulty on postural sway

Findings revealed a significant large-sized main effect of BTD ($p < 0.001$; $d = 6.36$) on postural sway in terms of total CoP displacements. More precisely, Bonferroni-corrected post-hoc comparison indicated that postural sway increased significantly with increasing levels of task difficulty ($p \leq 0.001$; $1.52 \leq d \leq 5.91$), except from level 1 to level 2 and from level 3 to level 4.

5.4. Effects of balance task difficulty on lower limb muscle activity and coactivation

Statistical analyses revealed significant large-sized main effects of task difficulty ($p < 0.001$; $2.19 \leq d \leq 4.88$) on the electromyographic activity of all selected muscles (i.e., TA, GM, PL, VM, BF). Post-hoc analyses with adjusted levels of significance for multiple comparisons showed that significant differences in electromyographic activity were mainly between low and high levels of task difficulty ($p \leq 0.043$).

Further, findings revealed significant large-sized main effects for task difficulty on aggregated ankle (TA, GM, PL; $p < 0.001$; $d = 2.93$) and thigh muscle activity (VM, BF; $p < 0.001$; $d = 2.54$), respectively. Bonferroni corrected post-hoc comparisons indicated significant differences in electromyographic activity between all levels of task difficulty ($p \leq 0.039$; $0.34 < d < 2.53$) except between levels 1 and 2 (thigh), between levels 3 and 4 (thigh), and between levels 5 and 6 (ankle, thigh).

In terms of muscle coactivation (i.e., CAI), the statistical analyses revealed significant large-sized main effects for muscles encompassing the ankle ($p = 0.002$, $d = 1.41$) and knee ($p = 0.005$, $d = 1.32$). Bonferroni corrected post-hoc comparisons showed significant differences ($p \leq 0.035$; $1.02 < d < 1.39$) between levels 1 and 6, between levels 2 and 5, and between levels 2 and 6.

The forward multiple regression analysis revealed a single best model ($p < 0.001$), with the ankle muscles as the best predictor ($r = 0.580$, $r^2 = 0.337$) for postural sway (i.e., CoP displacement) as a function of increasing task difficulty. Within the muscles encompassing the ankle, the TA was identified as the muscle that could predict postural sway the best ($p < 0.001$; $r = 0.570$, $r^2 = 0.325$). Potential confounders such as anthropometrics (i.e., height, body mass) had no impact on the results.

5.5. Effects of balance task difficulty on cortical activity

The k-means clustering algorithm identified five clusters of electrocortical sources in frontal, central (left, right), and parietal (left, right) areas of the brain. Cluster were composed out of 21-32 ICs from 11-13 participants.

Statistical analyses revealed significant large-sized main effects for BTD on absolute theta frequency band power in the frontal ($p < 0.001$; $d = 1.80$), central left ($p < 0.001$; $d = 1.49$), and central right clusters ($p < 0.001$; $d = 1.42$). More precisely, theta frequency band power increased significantly from baseline to low and high levels of task difficulty (frontal, central left, central right; $p \leq 0.029$; $0.07 < d < 0.3$) and from low levels to high levels of task difficulty (frontal, central left, and central right; $p \leq 0.05$; $0.08 < d < 0.29$) when adjusted post-hoc tests were applied.

In terms of absolute alpha-2 frequency band power, the analyses showed a significant large-sized main effect for BTD in the central right cluster ($p = 0.005$; $d = 0.92$) and a nonsignificant main effect in the central left cluster. Post-hoc analyses for level-dependent changes in absolute alpha-2 power revealed no significant differences between levels. Findings for the parietal left ($p < 0.001$; $d = 1.39$) and parietal right cluster ($p < 0.001$; $d = 1.05$) revealed significant large-sized main effects for task difficulty. More precisely, absolute alpha-2 power decreased significantly in both clusters from baseline to low and high levels of task difficulty ($p \leq 0.028$; $0.12 \leq d \leq 0.22$).

6. General discussion

In the present cumulative doctoral thesis, findings obtained from a systematic review with meta-analyses (Publication I) and two cross-sectional studies (Publication II and III) were incorporated to complement current knowledge on the effectiveness of BT and the impact of an increasing BTD on performance (i.e., postural sway), as well as neurophysiological (i.e., muscle activity and cortical activity) outcomes in youth. Overall, results of the meta-analysis indicate that BT is very effective in promoting balance performance in youth, but the observed training induced effects could not be predicted by any of the investigated training modalities. Findings from the cross-sectional studies revealed a decline in balance performance with a gradual increase in task difficulty. Concomitantly, neurophysiological outcomes changed as a function of an increase in task difficulty. More precisely, leg muscle activity, muscle coactivation, and fronto-central cortical activity within the theta frequency band increased with the level of task difficulty while alpha-2 frequency band activity in parietal brain areas decreased. The following section provides a brief interpretation and discussion of the main findings on the basis of the available body of literature.

6.1. Effects of balance training on balance performance in youth

The various effects of BT have been studied extensively in healthy young and old adults. A variety of studies, review articles, and meta-analyses showed the beneficial effects of BT in terms of balance performance improvements (Kümmel et al., 2016; Lesinski et al., 2015a, 2015b; Zech et al., 2010) and injury prevention (e.g., lower limb muscle and ligament injuries) (Lauersen et al., 2014; Mandelbaum et al., 2005). Regarding the youth population, the existing literature lacks in a comparable analysis quantifying the performance enhancing effects of BT. The findings of this thesis revealed moderate-to-large effects of BT on proxies of static and dynamic balance performance in children and adolescents, respectively, implying that it is a highly effective method to improve balance performance for this population. The present results were consistent with previously reported effects of BT on measures of static and dynamic balance in healthy young adults (Lesinski et al., 2015a), assuming that there are even marginal differences in effectiveness between the two age groups. Meta-analytical evidence from healthy older adults (Lesinski et al., 2015b) compared to those from healthy youth draw a slightly different picture. That is, BT appears to be more effective in children and adolescents as suggested by superior training induced effects in this population. Overall, findings of this thesis support Hypothesis 1a that BT is an effective means to improve static and dynamic balance performance in children and adolescents.

Additionally, the analyses of the moderating effects of sex, chronological age, training status, setting, and test method revealed no statistically significant impact on training-induced improvements of static and dynamic balance, which is in contradiction to Hypothesis 1b. Nevertheless, the respective subgroup analyses helped to identify potential sources accounting for the high heterogeneity observed in the meta-analyses. Particularly the heterogeneity in studies examining children and using physical fitness tests was considerably high. It can be assumed that this is caused by a large variability in children’s balance performance improvements, as well as a higher inaccuracy and error of measurement in investigator-administered physical fitness tests. However, the present result that selected moderator variables seem to have no influence on BT effectiveness must be considered as preliminary due to high between-study heterogeneity and poor methodological quality of many of the included studies. Besides this, a few recently published studies on BT-related age (Schedler, Brock et al., 2020; Wälchli et al., 2017) and sex differences (Schedler, Brueckner et al., 2020) in youth challenge these findings and support its tentative nature. For instance, Schedler, Brock et al. (2020) examined the effects of a 5-week BT program on static steady-state, dynamic steady-state, proactive and reactive balance in children aged 7-8 years and adolescents aged 14-15 years compared to active controls receiving their regular physical education. The authors reported larger improvements for static and dynamic steady-state balance but no significant differences in proactive and reactive balance in children compared to adolescents. They concluded that this may indicate a higher trainability in children for these balance components due to a larger adaptive reserve.

Further, Wälchli et al. (2017) reported significant improvements across three age groups (6-7 years, 11-12 years, 14-15 years) on static and dynamic balance performance after five weeks of child-oriented BT. Notably, the authors observed age-specific adaptations to the dynamic balance tasks, with the largest improvements in the youngest group. They concluded that the content of BT protocols should be tailored to the needs and demands of specific age groups in order to increase its effectiveness. In another study, Schedler, Brueckner et al. (2020) investigated sex-specific performance improvements in 32 boys and girls aged 8-9 years performing a stabilometer task after two consecutive days of practicing. Performance increases during two days of task acquisition tended to be larger in girls compared to boys. Moreover, girls showed a significantly better performance in the retention and automation test. Thus, practitioners should consider the sex-specific learning progress when designing BT programs with exercises of varying task difficulty and complexity. Overall, these recently reported findings imply that moderator variables like age and sex affect training-induced increases in balance component-specific performance, implying that contents of BT programs should account for the needs according to age and sex in youth. Thus, more research is needed to confirm and consolidate the potential impact of these moderator variables.

6.2. Dose-response relationship of balance training in adolescents

A large number of original studies examined the performance-enhancing effects of BT on balance components in youth (Bal, 2012; Boccolini et al., 2013; Dobrijević et al., 2016; Eisen et al., 2010; Emery et al., 2004; Filipa et al., 2010; Gioftsidou et al., 2006; Granacher et al., 2010; Granacher et al., 2011; Kollmitzer et al., 2000; Kubo et al., 2010; Pau et al., 2012; Schedler, Tenelsen et al., 2020; Wälchli et al., 2017). As part of the present thesis and for the first time in children and adolescents, these beneficial effects of BT were quantified systematically. Meta-analytical evidence presented in the previous section clearly indicates its general effectiveness on performance of static and dynamic balance components in youth. Findings in adolescents suggest a similar effectiveness, as BT had moderate-to-large ergogenic effects on static, dynamic, and overall balance. As pointed out previously, alleviated effects in adolescents might be explained by a smaller adaptive reserve and a more consistent performance level (i.e., smaller heterogeneity) compared to children. However, the question arises how BT protocols should be designed to optimize their effectiveness. To answer this, modality-specific subgroups were analyzed, and dose-response relationships were developed on the basis of the respective effect size magnitude. Due to the small number of child studies, dose-response relationships could only be established for adolescents. Analyses identified training periods of 12 weeks, a frequency of two training sessions per week, a session number of 24-36, a duration of 4-15 minutes, and a total duration of 31-60 minutes as the training modalities with the largest effect on overall balance performance in adolescents when considering each individually and not as a complementary training program. These dose-response relationships for adolescents had similar characteristics regarding the respective training modalities compared to those established for healthy young and old adults, which is in line with Hypothesis 2. Slight but apparent differences in training frequency (i.e., two times per week in adolescents vs. three times per week in young and older adults) and training volume (e.g., 4-15 minutes in adolescents vs. 31-45 minutes per single training session in old adults) might be attributed to longer periods of recovery necessary to avoid injuries due to fatigue or overuse in youth. Additionally, longer neuromuscular adaption processes in youth might also account for the observed deviations in comparison to adults.

In order to specify which of the examined training modalities are predictive for the effectiveness of BT programs, a multivariate random effects meta-regression was calculated. The non-significant results indicated that the training modalities included in the meta-regression model were not able to predict the effectiveness of BT. Additionally, the applied meta-regressional model was not able to explain the observed between-study variance ($R^2 = 0.00$). These findings suggest that there has to be another training modality not considered in the present thesis, which provokes the beneficial effects on balance performance. Such a key training modality could be training intensity and/or task difficulty. As intensity of BT is very difficult to assess and objectify (Farlie et al., 2013), BTD seems to be more promising regarding its practicability.

6.3. Effects of balance task difficulty on postural sway/balance performance

As stated in the previous section, it seems that BTD plays a key role concerning the effectiveness of BT. Concurrently, information on the implementation of gradual progression (e.g., via increasing task difficulty) into BT protocols is limited as compared to other training methods like, for instance, strength training. In this context, a first approach to evaluate the effects of an increasing BTD would be to analyze its impact on the performance of task execution (i.e., postural sway). So far, a few studies have examined the effects of an increasing BTD on postural sway only in healthy young (Cimadoro et al., 2013; Dohm-Acker et al., 2008; Muehlbauer et al., 2012; Muehlbauer et al., 2014) or between healthy young and old adults (Amiridis et al., 2003; Donath et al., 2016), indicating amplified postural sway as a result of more challenging postural demands. However, previously published studies (Amiridis et al., 2003; Cimadoro et al., 2013; Dohm-Acker et al., 2008; Donath et al., 2016; Muehlbauer et al., 2012; Muehlbauer et al., 2014) had in common that task difficulty was increased by changing various environmental conditions, which makes it hard to identify their contributions to an increase in task difficulty. In this context, mainly the factors of BoS, surface, vision, and training device were used and applied in varying constellations to achieve progression in task difficulty. For instance, Muehlbauer et al. (2012) investigated how an increasing task difficulty affects postural sway in young adults in order to establish a progression sequence for BT protocols. In this cross-sectional study, the authors manipulated environmental conditions by narrowing the BoS, increasing surface instability, and excluding visual information to achieve an increase in task difficulty during balance task execution. Overall, they analyzed the postural sway in twelve different levels of task difficulty by combining stance, stability, and visual conditions and found significant increases in postural sway. Based on their results, Muehlbauer et al. (2012) concluded that reductions in the BoS and the limitation of sensory information led to a progression in task difficulty. Especially under conditions where a considerably small BoS (i.e., unipedal, tandem) was combined with limited sensory information this progression could be observed as indicated by a much stronger increase in postural sway compared to conditions with a larger BoS (i.e., bipedal, step). Donath et al. (2016) investigated how five different levels of increasing task difficulty affected postural sway in young and old adults. Similar to Muehlbauer et al. (2012), the authors increased task difficulty by combining stance, stability, and visual conditions. Postural sway increased with higher postural demands in young and old adults, while increments in sway were higher with increasing task difficulty in old compared to young adults.

In contrast to these previous studies, the present doctoral thesis investigated the effects of a gradual increase of BTD on balance performance by manipulating only a single environmental condition (i.e., balance boards’ BoS) in adolescents. The results indicated that a systematic increase of task difficulty resulted in a significant, gradual increase in postural sway across all six levels. In addition, these findings were well in line with Hypothesis 3 and generally with the literature presented above. However, the amount of postural sway (i.e., absolute CoP displacements) seems to be much higher at every level of task difficulty in the examined adolescent population when a single environmental condition was manipulated compared to values reported by Muehlbauer et al. (2012) and Donath et al. (2016) for adults, where various conditions were combined and manipulated. A potential explanation could be that differences in postural sway between adolescents and adults might reflect ongoing nonlinear processes of growth and maturation, including the postural control system which is not fully developed before adolescence (Shumway-Cook & Woollacott, 1985; Steindl et al., 2006).

Summing up the results from this doctoral thesis it appears that a gradual increase in BTD through systematically reducing the BoS results in a graded increase in postural sway in a youth population (i.e., adolescents). Consequently, progression in BT can be easily implemented by increasing task difficulty through reducing the balance boards' BoS without the need for changing any other environmental condition.

6.4. Effects of balance task difficulty on lower limb muscle activity and coactivation

As postural control emerges from the complex interaction of the musculoskeletal and neural system, analyzing behavioral data in terms of postural sway paints only an incomplete picture of the effects of an increasing BTD on postural control. Thus, it is necessary to evaluate how the two involved systems responsible for maintaining or regaining balance adopt as a function of a systematic increase in task difficulty. A few studies have examined the effects of an increasing BTD on the musculoskeletal system by analyzing lower limb muscle activity focusing on healthy adult populations (Borreani et al., 2014; Cimadoro et al., 2013; Dohm-Acker et al., 2008; Donath et al., 2016; Licen et al., 2019; Muehlbauer et al., 2014). The majority of these studies indicated that activity of the ankle (Cimadoro et al., 2013; Dohm-Acker et al., 2008; Donath et al., 2016; Muehlbauer et al., 2014) and thigh muscles (Donath et al., 2016) increased with increasing task difficulty. Only Licen et al. (2019) and Dohm-Acker et al. (2009) reported no significant increases in ankle and thigh muscle activity, respectively. Further, previous studies found augmented muscle coactivation in muscles encompassing the ankle (Donath et al., 2016; Iwamoto et al., 2017) and knee joint (Donath et al., 2016) when postural demands increased. Thus, based on the majority of studies, it was hypothesized that lower limb muscle activity and coactivation increase with a gradual increase in BTD and that mainly ankle muscle activity explains task difficulty-related increments in postural sway.

The findings of the present doctoral thesis revealed a significant increase in electromyographic activity of all selected lower limb muscles (i.e., TA, GM, PL, VM, BF) and a significant increase in aggregated ankle (TA, GM, PL) and thigh muscle activity (VM, BF), as well as in muscle coactivation (CAI), with increasing levels of BTD in adolescents. Additionally, the ankle muscles, especially the TA muscle, seem to be the main contributor to postural control while maintaining balance on a multidirectional balance board with increasing levels of task difficulty. Overall, these findings were in conformance with Hypothesis 4. However, lower limb muscle activity continuously increased with BTD but tended to level off, as only marginal increases in muscle activity were observed between the two highest levels of task difficulty. Considering this and the results of Licen et al. (2019) and Dohm-Acker et al. (2008), who found no significant increases in ankle (Licen et al., 2019) and thigh muscle activity (Dohm-Acker et al., 2008) in a one-leg stance with increasing BTD, it appears that constant high activity of ankle and thigh muscles during high postural demands might be interpreted as a ceiling effect in lower limb muscle activity when the balance task difficulty exceeds a certain level. Concomitant with difficulty-related increases in lower limb muscle activity, muscle coactivation in terms of CAI values for muscles encompassing the ankle (TA, GM) and knee (VM, BF) rose from the lowest to the highest levels of task difficulty. Muscle coactivation is affected by several factors and increases for instance with age (Benjuya et al., 2004; Donath et al., 2015; Hortobagyi et al., 2009; Hortobágyi & Devita, 2000; Iwamoto et al., 2017; Kurz et al., 2018) and movement velocity (Hortobagyi et al., 2009; Iwamoto et al., 2017). Moreover, Iwamoto et al. (2017) and Donath et al. (2015, 2016) also reported increased muscle coactivation for the ankle (TA, m. soleus) and thigh muscles (VM, BF) with higher postural demands. In this context, stronger coactivation of agonistic and antagonistic muscle pairs can be interpreted as an indicator for increased joint stiffness. In highly posturally challenging situations, increased joint stiffness would result in increased postural stability accompanied by a concomitant reduction in freedom of movement. Consequently, it can be speculated that the present findings reflect a change in postural strategy from an ankle to a hip strategy from low to high levels of BTD to compensate for the increasing difficulty (Donath et al., 2016).

To summarize the findings of the present doctoral thesis, a gradual increase in BTD through reducing the balance boards' BoS results in increased electromyographic activity of the ankle and thigh muscles, as well as in increased coactivation of the muscles encompassing the ankle and knee. Moreover, the compensatory mechanisms contributing to the regulation and sustainment of postural stability seem to be mainly located at the ankle. However, these compensatory mechanisms appear to shift from the ankle to the hip when the level of BTD increases.

6.5. Effects of balance task difficulty on cortical activity

To complement the way in which the postural control system is affected by a gradually increasing BTD, the adaptive responses of the neural system need to be considered as well. Results from previous cross-sectional studies in adults (Nandi et al., 2018; Papegaaij et al., 2016;

Tokuno et al., 2018) using TMS assumed stronger cortical contributions under increasing postural demands as intracortical inhibition decreased with higher demands. Further, a few EEG-based studies indicate increased cortical activity reflected by spectral power changes in several frequency bands while postural tasks during static (Edwards et al., 2018; Hülsdünker, Mierau, Neeb et al., 2015; Hülsdünker, Mierau & Strüder, 2015; Peterson & Ferris, 2018; Slobounov et al., 2009; Solis-Escalante et al., 2019; Tse et al., 2013) and dynamic conditions (Peterson & Ferris, 2018; Sipp et al., 2013; Wagner et al., 2016) became more challenging in adults. In this context, Hülsdünker, Mierau, Neeb et al. (2015), Hülsdünker, Mierau & Strüder (2015), and Edwards et al. (2018) reported increased theta frequency band power at fronto-central electrode sites (Edwards et al., 2018; Hülsdünker, Mierau, Neeb et al., 2015; Hülsdünker, Mierau & Strüder, 2015), as well as decreased alpha frequency band power at centro-parietal electrode sites (Edwards et al. 2018, Hülsdünker, Mierau & Strüder 2015) when BTD increased through manipulation of several environmental conditions (i.e., BoS, surface, vision). Based on these previous findings, it was hypothesized that a gradual increase in BTD (i.e., only reducing the balance board's BoS) would result in frequency specific power changes in frontal, central, and parietal brain areas in adolescents. Specifically, difficulty-related increases in theta and decreases in alpha- 2 frequency band power in fronto-central and centro-parietal brain areas, respectively, were expected.

Consistent with Hypothesis 5, the findings of the present doctoral thesis revealed significant changes in cortical activity in frontal, central, and parietal brain areas in adolescents. More precisely, theta frequency band power increased significantly within clusters of electrocortical sources located in frontal and central areas of the brain with increasing BTD, while alpha-2 frequency band power decreased significantly in central and parietal clusters. With respect to the theta frequency band, observed increases in power in the frontal and central brain areas correspond to results of previously published studies (Edwards et al., 2018; Hülsdünker, Mierau, Neeb et al., 2015; Hülsdünker, Mierau & Strüder, 2015; Sipp et al., 2013; Slobounov et al., 2009; Varghese et al., 2014) that analyzed cortical contributions to postural control under various postural challenges. For instance, Slobounov et al. (2009) reported increases in frontal and central theta power after unpredictable perturbations during quiet single leg stance and identified the anterior cingulate cortex as a common source for perturbation-induced theta power increases. The authors concluded that the anterior cingulate cortex may serve as a monitoring and error-detection system for postural stability. Varghese et al. (2014) obtained similar results, observing fronto-central theta power increases after unpredictable perturbations during quiet bipedal stance and assumed that high-level cortical processing was involved in monitoring postural stability. Moreover, Sipp et al. (2013) reported increased theta power in several clusters of electrocortical sources located near or in the anterior cingulate, anterior parietal, dorsolateral prefrontal, and sensorimotor cortex during walking on a balance beam compared to walking on a treadmill, indicating increased attentional processes responsible for successful balance beam walking performance. When participants lost balance, theta power immediately increased in cortical sources located, among others, near or in the anterior cingulate and anterior parietal cortex but returned to baseline levels after regaining balance. The authors suggested that theta band activity might reflect ongoing error-detection processes during the monitoring of postural stability. In the context of an increasing BTD, Hülsdünker, Mierau, Neeb et al. (2015), Hülsdünker, Mierau & Strüder (2015), and Edwards et al. (2018) reported increasing theta band frequency power at central electrodes in healthy adults performing continuous balance tasks of increasing difficulty in upright stance by modulating the BoS, surface stability, and vision. Additionally, Hülsdünker, Mierau, Neeb et al. (2015) and Hülsdünker, Mierau & Strüder (2015) reported similar theta power increments at frontal electrodes. All three, Hülsdünker, Mierau, Neeb et al. (2015), Hülsdünker, Mierau & Strüder (2015), and Edwards et al. (2018) attributed the anterior cingulate cortex and sensorimotor areas as responsible for these theta power increases at frontal and central electrode sites. Overall, findings from the aforementioned studies may suggest the presence of a balance-specific cortical network which is further supported by recent work from Solis-Escalante et al. (2019) and Varghese et al. (2019). For instance, Solis-Escalante et al. (2019) described multifocal theta power bursts after postural perturbations in bipedal upright stance and interpreted these bursts as cortical network activity monitoring postural stability and making postural adjustments if necessary. Likewise, Varghese et al. (2019) interpreted their results as the presence of a complex cortical network linked to postural control and found rapid and transient reorganization of functional cortical networks between several brain areas and across delta, theta, alpha, and beta frequency bands when simulating unpredicted forward falls. With reference to these studies, the findings of the present doctoral thesis may support the hypothesis of a cortical network highly involved in postural control when maintaining and regaining balance. Increases in theta frequency power within clusters of electro-cortical sources located in frontal (anterior cingulate cortex) and central areas (sensorimotor areas) of the brain with increasing BTD may indicate a higher information processing load as a function of increased postural demands.

Interestingly, theta frequency band power in the frontal cluster tended to level off at very high levels of task difficulty. This phenomenon was previously described by Hülsdünker, Mierau, Neeb et al. (2015) and Edwards et al. (2018) as a “ceiling effect,” when postural demands exceed the capacities of the postural control system to maintain or regain balance. Since increased frontal theta power is also linked to increased attention in various tasks (Baumeister et al., 2008; Baumeister et al., 2013; Slobounov et al., 2000; Smith et al., 1999) , the present findings may be associated with increased focused attention and task-specific effort (Baumeister et al., 2008; Smith et al., 1999). Thus, increased frontal theta power may reflect increased attention and effort until capacities of the postural control system are insufficient to cope with increasing levels of BTD and frontal theta power remains on a plateau. Consequently, future research should investigate whether online measured theta power over frontal and/or central areas can be used as an indicator of too low, optimal, and excessive training demands of a balance exercise, similar to the methodological approach of EEG neurofeedback used for the treatment of attention-deficit/hyperactivity disorder in children and adolescents (van Doren et al., 2019).

Furthermore, and well in line with Hypothesis 5, findings of this doctoral thesis revealed a significant decrease in alpha-2 frequency band power within clusters of electro-cortical sources located in bilateral central and parietal areas of the brain following gradual increases in BTD. This is consistent with Edwards et al. (2018) and Hülsdünker, Mierau & Strüder (2015), who found decreases in broad alpha frequency band (8-12 Hz) as well as alpha-2 frequency band power (10-12 Hz), respectively, over centro-parietal electrodes when increasing postural demands of a balance task. Both research groups suggested that observed alpha power decreases reflect increased sensory information processing, as previous studies had shown that decreases in alpha power, especially alpha-2, indicate task-specific information processing (Del Percio et al., 2007; Del Percio et al., 2009; Klimesch et al., 2006; Leocani et al., 1997; Pfurtscheller et al., 1996; Slobounov et al., 2009). Additionally, Sipp et al. (2013) were able to identify the origin of broad alpha frequency band power decreases near or in the left and right sensorimotor cortex during balance beam walking. With reference to the literature, reductions in alpha-2 power in mainly parietal areas of both hemispheres may reflect increased sensory and movement-related information processing with a graded increase in task difficulty.

Taken together, a gradual increase in BTD led to frequency-specific power changes (theta↑, alpha-2↓) in frontal, bilateral central, and bilateral parietal cortical areas. The observed alterations in cortical activity suggest an increased involvement of cortical structures responsible for attentional and error-related processes as well as for sensory and movement-related information processing which contribute to the maintenance of postural control under challenging environmental conditions.

6.6. Limitations

Publications I, II, and III contributing to this cumulative doctoral thesis have a few potential limitations that warrant discussion. Only the main limitations of all three publications will be mentioned here, whereas a detailed discussion of all limitations is given in the “Limitations” section of each publication. Concerning the systematic review and meta-analysis (Publication I), the strongest limitation is the high-to-considerable heterogeneity between the included studies. Even though possible sources causing this heterogeneity were identified through subgroup analysis, future studies should use biomechanical tests for balance performance assessment and report standardized balance outcomes according to the four balance components proposed by Shumway-Cook and Woollacott (2012). Due to this heterogeneity, either some performance outcomes could not be clearly assigned to a balance component (e.g. quasi-dynamic balance), or performance outcomes for a balance component (e.g., proactive balance) were underrepresented in the included studies. Thus, these outcomes were merged into a more global category (i.e., dynamic balance), making it unfeasible to draw conclusions for the respective balance components. Further, dose-response relationships were calculated for each training modality independently without considering interactions between modalities. It is imperative to address these interaction effects in future research. Finally, studies of high methodological quality are needed to complement the current knowledge on the component-specific effects on BT in youth and to establish integrated dose-response relationships for each balance component.

In view of the two cross-sectional studies (Publications II and III), the main limitations are of a methodological nature. Additional kinematic (e.g., knee angles) and electromyographic data (e.g., hip/abdominal muscle) would have helped to provide clearer evidence for a difficulty-related change in postural strategy. Thus, it has to be noted that the assumption as to whether or not the postural strategy changes with increasing BTD (Publication I) remains speculative due to the lack of additional kinematic and electromyographic data. Moreover, high-density EEG (e.g., 128 EEG channels or above) recordings with co-registration and corresponding MRI imaging would have increased the precision of electrocortical source localization. However, the 64-channel EEG system used (Publication II) met the basic requirements for applying an ICA-based technique of source space localization (Sohrabpour et al., 2015). This EEG-signal processing technique is well-established in (exercise) neuroscience and has been frequently used in the literature (Anders et al., 2018; Büchel et al., 2021; Gwin et al., 2011; Sipp et al., 2013).

7. Conclusions

This doctoral thesis aggregates the findings of three publications that investigated the effects of BT on balance performance in youth, as well as the effects of an increasing BTD on balance performance, lower limb muscle activity, and cortical activity. In summary, the main results of the three publications can be summarized as follows:

1. BT is a highly effective means to improve balance performance, with moderate to large effects on static and dynamic balance in healthy youth irrespective of age, sex, training status, setting, and testing method. The examined training modalities did not have a moderating effect on balance performance in healthy adolescents.

2. When training modalities are considered individually, training periods of 12 weeks, a frequency of two sessions per week, a total of 24–36 sessions, durations of 4–15 min for a single training session, and total durations of 31–60 min of BT per week were the most effective single training modalities for balance improvement. Notably, none of the investigated training modalities is predictive for the beneficial effects of BT on balance performance.

3. Postural sway increased with a gradually increasing BTD. Based on the postural data, a gradual increase in BTD through a systematic reduction of the BoS can be easily applied with the BT device used in ths study.

4. Lower limb muscle activity and muscle coactivation increased with a gradually increasing BTD. In addition to postural data, lower limb electromyographic activity indicates that a gradual increase in BTD through a systematic reduction of the BoS can be easily applied with the BT device used in this study. Further, increased muscle coactivation allows speculation on a difficulty-dependent change in postural strategy from an ankle to a hip strategy.

5. Following gradual increases in BTD, cortical activity in terms of theta frequency band power within clusters of electrocortical sources in frontal and bilateral central areas of the brain increased, while alpha-2 frequency band power within clusters of electro-cortical sources located in bilateral central and parietal areas of the brain decreased. These findings

may reflect a higher information processing load in the anterior cingulate cortex and sensorimotor areas as well as increased sensory and movement-related information processing with a graded increase in BTD.

8. Practical implications

The present doctoral thesis and its findings aimed to fill the identified gaps in the literature regarding the effectiveness of BT and the effects of an increasing BTD on balance performance and neurophysiological outcomes in youth. Several practical implications of high interest for coaches, teachers, practitioners, and youth (athletes) can be drawn on the basis of the presented results concerning the application of BT and the implementation of BTD.

Findings from Publication I revealed that BT is a highly effective method to improve balance performance in youth irrespective of age, sex, training status, setting, and testing methods. Thus, BT should be a fundamental part of physical education and regular training. It can be easily integrated in warm-up protocols, for instance, as the greatest effects on balance performance were observed for durations of 4 – 15 minutes per single training session. Furthermore, findings from Publication I complement the already existing practical recommendations for BT in healthy young and old adults for a healthy adolescent population (Table 1).

Table 1 Dose-response relationship for balance training and it's training modalities in healthy adolescents (Gebel et al., 2018) compared to the respective dose-response relationship in healthy young (Lesinski et al., 2015a) and old adults (Lesinski et al., 2015b) adapted by Gebel et al. (2018). Training modalities that were analyzed only in young adults were excluded from this table.

Training modalities[a]	Results/most effective dose			
	Healthy adolescents (mean age 12-19 yrs)	Healthy young adults (age 16-40 yrs)	Healthy old adults (age +65 yrs)	
	Overall balance (13 studies included)	Static/dynamic steady-state balance (16 studies included)	Overall balance (23 studies included)	Static steady-state balance (12 studies included)
Training period (weeks)	12	11-12	11-12	11-12
Trainings frequency (times per week)	2	3	3	3
Number of training sessions	24-36	16-19, 36-39[b]	36-40	36-40
Duration of a single training session (min)	4-15	11-15[c]	31-45	31-45
Total duration of BT per week (min)	31-60	N/A	91-120	121-150[d]

BT balance training, *N/A* not available; *yrs* years

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[a] Training modalities were calculated independently (i.e., modality-specific) and have to be considered individually.

[b] Almost identical effect sizes (1.12 vs. 1.09)

[c] Most included studies performed BT without warm up and/or cool down and thus were shorter in duration compared to youth and old adults.

[d] Only one study

Findings from Publications II and III revealed that an increasing difficulty of a balance task based on a graded reduction of the BoS results in increased postural sway, lower limb muscle activity, coactivation, and cortical activity. Given these findings, reducing the balance board's BoS is a highly sufficient and easily applicable method to increase postural task demands, helping to individualize the implementation of progression into BT in the fields of rehabilitation, athletic development, and physical education. Considering that successful performance of balance tasks requires the involvement of frontal, central, and parietal cortical structures along with more cortical resources for focusing attention as well as sensory and movement-related information processing when the level of task difficulty increases, balance tasks need to be trained at an adequate level of task difficulty. Thus, adaptive processes within respective cortical areas will be induced, resulting in higher "neural efficiency" (Del Percio et al., 2009) and unblocking of cortical resources which could then be allocated to other tasks (e.g., dual-, multi-tasking) (Sauseng et al., 2007).

9. Future directions

Even though this thesis aimed to fill the gaps identified in the literature concerning the effectiveness of BT as well as the effects of an increasing BTD on balance performance and neurophysiological outcomes in youth, some issues still remain unsolved. Based on the findings of the present doctoral thesis, objectives for future research projects related to BT and task difficulty, its effects on neurophysiological outcomes, and potential adaptive cortical processes in youth can be formulated as follows:

a) In view of the practical recommendations in Table 1, which consider only adolescents and are based on balance performance outcomes of different balance components (e.g., static steady-state, proactive), more research of high methodological quality (i.e., randomized controlled trials) in children and adolescents is needed that elucidates the effects of a balance-component-specific training regimen. Additionally, based on these studies it would be possible to establish component-specific dose-response relationships for both children and adolescents.

b) In addition to meta-analyses and dose-response analyses, more comparative studies are needed to examine the effects of a single training modality while the other modalities are kept constant. This would allow conclusions to be drawn regarding interactions between the different training modalities and help identify the most relevant training modalities for BT in youth

c) It remains speculative whether the postural strategy changes with BTD. Thus, future studies should focus on the difficulty-dependent change of postural strategy by examining and analyzing kinematic, kinetic, electromyographic, and electroencephalographic data in a more holistic approach.

d) The findings from Publication III clearly indicate involvement of several cortical areas during the performance of a balance task in addition to the finding that the activity in the involved cortical areas increases with task difficulty. However, it remains unclear just how much spinal reflexes and supraspinal centers contribute to postural control when BTD increases. Taube and Gollhofer (2011) assumed in this context that supraspinal contributions would increase, as higher postural demands require more cortical control to maintain balance. Thus, future studies should use high-density EEG systems to specify these functional areas, their time–frequency characteristics, and cortical network activity during increasing instability, as well as cortico-muscular coherence analysis to link cortical contributions to muscle activation patterns during increasing postural demands. Furthermore, future research should investigate whether online measured theta power over the frontal and/or central areas can be used as an indicator for insufficient, optimal, and excessive training demands of BTD to improve BT monitoring.

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Author’s contribution

The present doctoral thesis is designed as a cumulative dissertation. Consequently, three scientific articles have been submitted to international peer-reviewed journals and accepted for publication. According to the doctoral degree regulations of the Human Sciences Faculty of the University of Potsdam (§ 7 (4), sentence No. 2), significant contributions to the articles from the respective co-authors were acknowledged and confirmed by each co-author.

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Arnd Sebastian Gebel

Titel der Dissertation:

Postural control in youth: From performance to neural correlates

Betreuer/in:
Prof. Dr. Urs Granacher

Wissenschaftliche Abhandlung 1

Titel	Effects and dose-response relationship of balance training on balance performance in youth: a systematic review and meta-analysis
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Journal	Sports Medicine
	Publikationsstatus (bitte ankreuzen)
(x)	Nicht eingereicht
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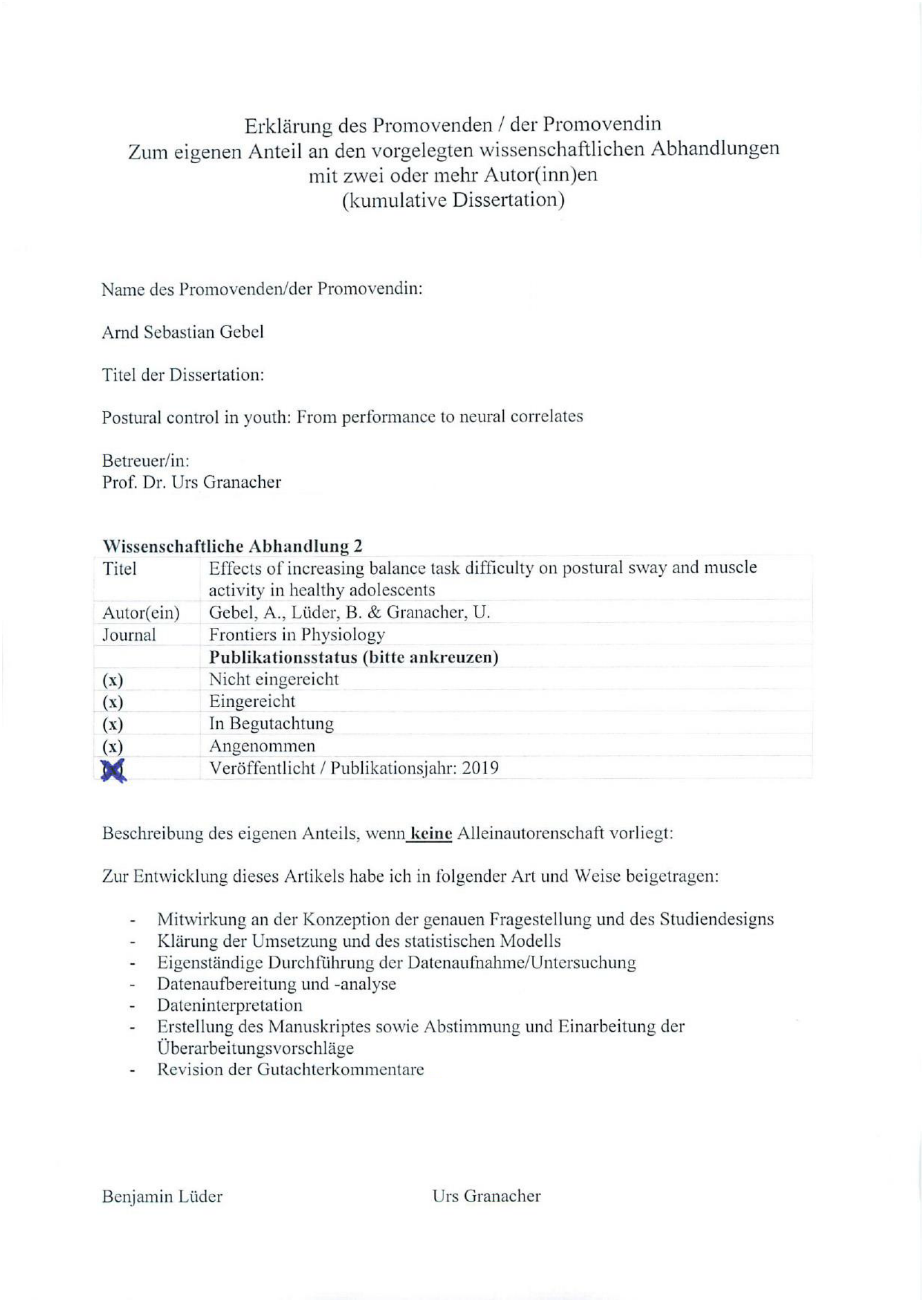
- Datenaufbereitung und -analyse
- Dateninterpretation
- Erstellung des Manuskriptes sowie Abstimmung und Einarbeitung der Überarbeitungsvorschläge
- Revision der Gutachterkommentare

Melanie Lesinski David Behm Urs Granacher



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Wissenschaftliche Abhandlung 2

Titel	Effects of increasing balance task difficulty on postural sway and muscle activity in healthy adolescents
Autor(ein)	Gebel, A., Lüder, B. & Granacher, U.
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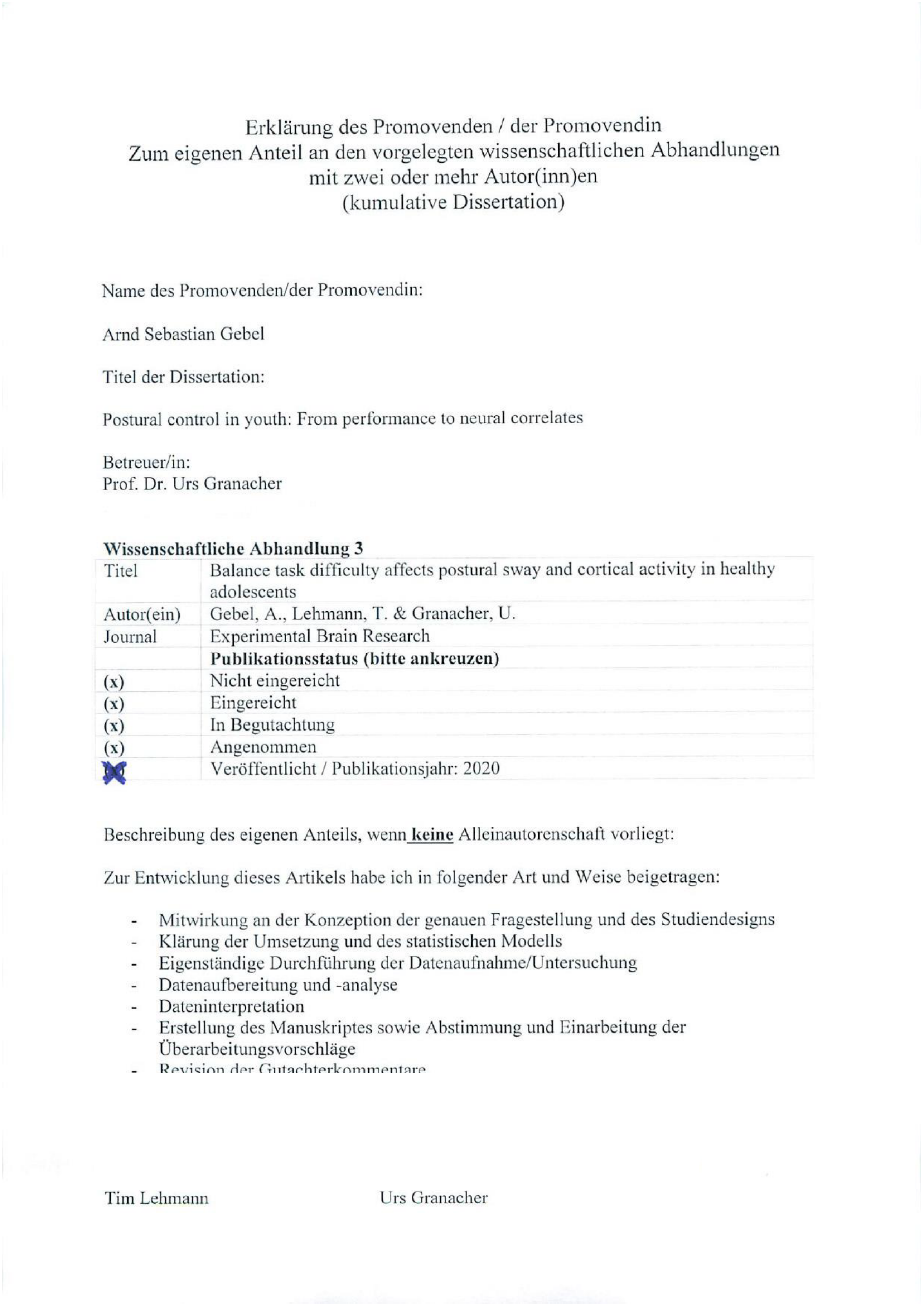

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Wissenschaftliche Abhandlung 3

Titel	Balance task difficulty affects postural sway and cortical activity in healthy adolescents
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- Datenaufbereitung und -analyse
- Dateninterpretation
- Erstellung des Manuskriptes sowie Abstimmung und Einarbeitung der Überarbeitungsvorschläge
- Revision der Gutachterkommentare

Tim Lehmann Urs Granacher

Publication I

EFFECTS AND DOSE-RESPONSE RELATIONSHIPS OF BALANCE TRAINING ON BALANCE PERFORMANCE IN YOUTH: A SYSTEMATIC REVIEW AND META-ANALYSIS

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Effects and dose-response relationship of balance training on balance performance in youth: A systematic review and meta-analysis

Running title: Balance training in youth

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Abstract

Background:

Effects and dose-response relationships of balance training on measures of balance are well-documented for healthy young and old adults. However, this has not been systematically studied in youth.

Objectives:

The objectives of this systematic review and meta-analysis were to quantify effects of balance training (BT) on measures of static and dynamic balance in healthy children and adolescents. Additionally, dose-response relations for BT modalities (e.g., training period, frequency, volume) were quantified through the analysis of controlled trials.

Data Sources:

A computerized systematic literature search was conducted in the electronic databases PubMed and Web of Science from January 1986 until June 2017 to identify articles related to BT in healthy trained and untrained children and adolescents.

Study Eligibility Criteria:

A systematic approach was used to evaluate articles that examined the effects of BT on balance outcomes in youth. Controlled trials with pre- and post-measures were included if they examined healthy youth with a mean age of 6-19 years and assessed at least one measure of balance (i.e., static/dynamic steady-state balance, reactive balance, proactive balance) with behavioural (e.g., time during single-leg stance) or biomechanical (e.g., centre of pressure displacements during single-leg stance) test methods.

Study Appraisal and Synthesis Methods:

The included studies were coded for the following criteria: training modalities (i.e., training period, frequency, volume), balance outcomes (i.e., static and dynamic balance) as well as chronological age, sex (male vs. female), training status (trained vs. untrained), setting (school vs. club), and testing method (biomechanical vs. physical fitness test). Weighted mean standardized mean differences (SMD_{wm}) were calculated using a random-effects model to compute overall intervention effects relative to active and passive control groups. Between-study heterogeneity was assessed using I^2 and χ^2 statistics. A multivariate random effects meta-regression was computed to explain the influence of key training modalities (i.e., training period, training frequency, total number of training sessions, duration of training sessions, and total duration of training per week) on the effectiveness of BT on measures of balance performance. Further, subgroup univariate analyses were computed for each training modality.

Additionally, dose-response relationships were characterized independently by interpreting the modality specific magnitude of effect sizes. Methodological quality of the included studies was rated with the help of the Physiotherapy Evidence Database (PEDro) Scale.

Results:

Overall, our literature search revealed 198 hits of which 17 studies were eligible for inclusion in this systematic review and meta-analysis. Irrespective of age, sex, training status, sport discipline, and training method, moderate to large BT-related effects were found for measures of static (SMD_{wm} = 0.71) and dynamic (SMD_{wm} = 1.03) balance in youth. However, our subgroup analyses did not reveal any statistically significant effects of the moderator variables age, sex, training status, setting, and testing method on overall balance (i.e., aggregation of static and dynamic balance). BT-related effects in adolescents were moderate to large for measures of static (SMD_{wm} = 0.61) and dynamic (SMD_{wm} = 0.86) balance. With regard to the dose-response relations, findings from the multivariate random effects meta-regression revealed that none of the examined training modalities predicted the effects of BT on balance performance in adolescents ($R^2 = 0.00$). In addition, results from univariate analysis have to be interpreted with caution because training modalities were computed as single factors irrespective of potential between-modality interactions. For training period, 12 weeks of training achieved the largest effect (SMDwm = 1.40). For training frequency, the largest effect was found for two sessions per week (SMDwm = 1.29). For total number of training sessions, the largest effect was observed for 24-36 sessions (SMDwm = 1.58). For the modality duration of a single training session, 4-15 minutes reached the largest effect (SMDwm = 1.03). Finally, for the modality training per week, a total duration of 31-60 min per week (SMDwm = 1.33) provided the largest effects on overall balance in adolescents. Methodological quality of the studies was rated as moderate with a median PEDro score of 6.0.

Limitations:

Dose-response relationships were calculated independently for training modalities (i.e., modality specific) and not interdependently. Training intensity was not considered for the calculation of dose-response relationships because the included studies did not report this training modality. Further, the number of included studies allowed the characterization of dose-response relationships in adolescents for overall balance only. In addition, our analyses revealed a considerable between-study heterogeneity (I^2 = 66-83%). The results of this meta-analysis have to be interpreted with caution due to their preliminary status.

Conclusions:

BT is a highly effective means to improve balance performance with moderate to large effects on static and dynamic balance in healthy youth irrespective of age, sex, training status, setting, and testing method. The examined training modalities did not have a moderating effect on balance performance in healthy adolescents. Thus, we conclude that an additional but so far unidentified training modality may have a major effect on balance training that was not assessed in our analysis. Training intensity could be a promising candidate. However, future studies are needed to find appropriate methods to assess balance training intensity.

Key Points:

This systematic review and meta-analysis quantified the effects and dose-response relationships following balance training (BT) in youth. We found that BT is an effective means to improve balance irrespective of age, sex, training status, setting, and testing method.

Our dose-response analyses that the examined training modalities (e.g. training period, training frequency) did not have a moderating effect on balance performance in healthy adolescents. Thus, it appears that an additional but so far unidentified training modality (e.g. training intensity) could be a likely agent.

Future studies are needed to elucidate relevant BT-modalities that allow the analysis of dose-response relationships following BT in youth.

1 Introduction

Balance is an important prerequisite for learning complex motor skills during childhood [1, 2] and the foundation for a successful performance of everyday and sport-related activities from youth to adulthood. In two recent review articles addressing the relationship of balance, sports expertise, and performance, Hrysomallis [3] and Kiers et al. [4] stated that improved balance performance is associated with increased physical activity and athletic performance (i.e., vertical jumping, sprinting, change-of-direction tasks). Moreover, these authors postulated that superior balance performance in sport-specific conditions is an important prerequisite to become a high-level athlete. For instance, in highly dynamic situations in sports like basketball, handball, volleyball, and soccer, which afford rapid changes-of-direction, vertical and horizontal jumping, proper dynamic alignment of the centre of mass (CoM) relative to the base of support is essential for successful performance [5, 6]. However, CoM misalignment is related to impaired force transmission from the feet to the trunk and upper body, which again results in compromised performance [7, 8]. This balance-performance relationship is also exemplified in winter sports, as maximum skating speed was significantly correlated with static balance in youth hockey players [9]. In this context, a number of reviews have reported on the effectiveness of instability training, reporting that the force output under unstable compared to stable conditions is lower (approximately 30%) due to the inability to maintain the CoM over the base of support [7, 10, 11].

A growing body of the literature [3, 12, 13] provides evidence that balance training (BT) has the potential to counteract these impairments under dynamic conditions. For instance, Yaggie et al. [12] showed that BT in young adults not only improved balance performance but also promoted performance in highly dynamic sport-related activities (i.e., shuttle run). Moreover, Mahmoud [13] demonstrated a positive effect of BT on sport-related performance by improving selected sport-related skills (e.g., dribbling and passing on wall targets, shooting around the free throw zone) in youth basketball players. Conversely, if balance is not adequately developed and trained during youth, it may limit the inherent adaptive potential in sport-related tasks and it may also increase the risk of sustaining injuries.

Currently, a systematic analysis of the literature on BT in youth is lacking, which is why it is timely and imperative to statistically aggregate findings from the literature in the form of a meta-analysis on the effects of BT on measures of balance in youth. Similar approaches were recently published for healthy young [14] and old adults [15]. Another systematic review compared BT effects with those of resistance and/or plyometric training [16]. Further, Kümmel et al. [17] examined in their review whether BT effects are specific to the trained task or whether they were transferable to non-trained balance tasks as well.

Therefore, the objectives of this systematic review and meta-analysis were to quantify the general effects of BT on static and dynamic balance in youth and to examine the influence of moderator variables like sex, age, training status, setting, and testing method on training-induced balance outcomes. In addition, we aimed to characterize dose-response relationships of BT modalities (i.e., training period, frequency, and volume) through controlled trials that maximize improvements in balance performance in youth. Based on findings of single (randomized) controlled trials, we hypothesized that BT is an effective means to improve static [18, 19] and dynamic balance performance [20, 19] in youth. Further, we expected that BT effectiveness on measures of balance is affected by the moderator variables (i.e., age, sex, training status, setting, and testing method) [21, 1, 3]. With reference to the findings of Lesinski and colleagues regarding dose-response relationships following BT in healthy young [14] and old [15] adults, we hypothesized that dose-response relationships for training modalities (i.e., training volume) in youth are comparable to those in adults.

2 Methods

In this study, the authors followed the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement guidelines [22].

2.1 Literature Search

The authors conducted a systematic computerised literature search in the electronic databases PubMed and Web of Science. In accordance with Lesinski et al. [14, 15], the following Boolean search syntax was used: ("balance training" OR "neuromuscular training" OR "balance exercise" OR "proprioceptive training" OR "sensorimotor training" OR "instability training" OR "perturbation training") AND (children OR adolescent* OR youth OR puberty OR kids OR teen* OR girl* OR boy*) NOT (disease OR disorder OR syndrome OR patient OR old OR older OR elderly OR adult) and adapted for our target population.

In addition, the following filters were applied: text availability: full-text; publication dates: 01/01/1986 to 06/30/2017, species: humans, ages: 6-12 years (children), 13-18 years (adolescents); languages: English, German. The search syntax used for the PubMed database was adapted for the Web of Science database. Moreover, reference lists of each article and relevant review articles [14, 23-32] were scrutinized to identify additional adequate references for this systematic review and meta-analysis.

2.2 Selection Criteria

Studies were considered eligible to be included in this review if they provided relevant information with regards to the PICOS (participants, interventions, comparators, outcomes, and study design) approach [33] and were in accordance with the following predefined inclusion criteria: (1) population: healthy youth (i.e., children and adolescents) with a mean age of 6-19 years (age range was defined on the basis of age limits for children and adolescent as recommended by Malina et al. [34]); (2) intervention: BT protocols comprising static/dynamic postural stabilization exercises; (3) comparator: active or passive control groups (i.e., age-matched subjects completing their regular training routine, an alternative training or no training); (4) outcome: at least one measure of balance (i.e., static/dynamic steady-state balance, reactive balance, proactive balance) assessed with behavioural (e.g., time during single-leg stance) or biomechanical (e.g., centre of pressure displacements during single-leg stance) test methods (5) study design: controlled trials with a pre- and post-measures. Studies were excluded when (1) they examined youth with health deficits or did not correspond to the mean age range from 6-19 years; (2) BT was combined with resistance training, endurance training, plyometrics, and/or stretching exercises, examined only one specific type of BT (e.g., slackline, exergames) or involved fewer than 6 training sessions; (3) BT effects were examined without control; (4) they reported no means and standard deviations/errors in the results section as text/graphic or upon inquiries; (5) study design was not a (randomized) controlled trial. Two independent reviewers (AG, ML) screened potentially relevant papers by analysing titles, abstracts, and full texts of respective articles to determine their eligibility. When AG and ML did not reach an agreement concerning inclusion of an article, UG was consulted for clarification.

2.3 Coding of Studies

All included studies were coded for the following variables as listed in Table 1. Additionally, for reasons of dose-response relationship characterization, BT was coded for the following training modalities: training period, training frequency, total number of training sessions, duration of a single training session, and total duration of training per week. Grouping within the training modalities was done according to Lesinski et al. [14, 15] to enable comparability. Since there are no psychometrically validated tools to measure the intensity of balance exercises and how they challenge postural control [35], the training modality “training intensity” was not coded.

According to Shumway-Cook and Woollacott [36] balance is highly task-specific and therefore should be subdivided in the following components: static/dynamic steady-state balance (e.g., maintaining a steady position in standing, walking, and running), proactive balance (e.g., anticipation of a predicted postural disturbance/perturbation), and reactive balance (e.g., compensation for an unexpected perturbation). None of the included studies reported measures of dynamic-steady state balance (e.g., 10-m gait speed test) and reactive balance (e.g., CoP displacement after unexpected perturbations) and only a limited number of studies reported measures of proactive balance (i.e., Star Excursion Balance Test). Thus, outcomes involving proactive balance and tests incorporating quasi-dynamic conditions (e.g., balancing on unstable surface) were aggregated as measures of dynamic balance to obtain sufficient statistical power for our quantitative analysis. In this context, static steady-state balance (e.g., CoP displacements during single leg stance on a stable surface) is referred to as static balance to improve readability of this article. Therefore, the focus of this analysis was on the following outcome components: (1) static and (2) dynamic balance. When multiple variables were reported within one component, only one representative was used for quantitative analyses. In case of multiple variables reported for dynamic balance a decision tree was applied that prioritized the importance of the test instrument to assess functional capacity: (a) proactive balance, (b) quasi-dynamic conditions. Preferred variables for the outcome components are defined in Table 1.

Table 2 Study coding

Chronological age	Children (boys: ≤ 9 years; girls ≤ 7 years) [34] Adolescents (boys: 10-19 years; girls: 8-19 years)[34]
Outcome components	Static balance (i.e., static steady-state balance; preferred CoP path length in single leg stance for 30 s, stable ground, eyes opened, dominant leg) Dynamic balance (i.e., proactive balance and quasi-dynamic conditions; preferred Star Excursion Balance Test)
Setting	Sports club School
Sex	Male youth Female youth
Method	Biomechanical tests Physical fitness tests
Status of training	Trained (i.e., trains systematically more than once per week; and has more than 1 year competition history) [70] Untrained

s seconds, *CoP* centre of pressure

Due to the scarce number of studies reporting measures of both static and dynamic balance undercutting the critical mass for further analyses, the impact of moderator variables and BT dose-response relationships were computed for overall balance. When measures for both, static and dynamic balance were reported, test instruments assessing dynamic balance were prioritized in consideration of the decision tree as defined above. Relevant data that were only reported in figures were extracted from these using GetGraph Graph Digitizer (http://www.getdata-graph-digitizer.com/index.php) when authors did not respond to our inquiries for original data. The validity of the extracted data was verified by another reviewer (ML).

2.4 Assessment of Methodological Quality and Statistical Analyses

The Physiotherapy Evidence Database (PEDro) scale was used to assess the risk of bias in eligible studies and to rate the methodological quality of studies on a scale from 0 to 10. A score of 6 or higher, marking a cut-off score, indicates a high study quality [37, 38]. If available, PEDro scores were retrieved from the PEDro database [39]. Further, risk of bias across studies (i.e., publication bias) was checked by visual inspection of the funnel plots. An asymmetrical funnel plot with the smallest studies showing larger effects indicates a publication bias [40].

To assess the effectiveness of BT on proxies of static and dynamic balance performance for children and adolescents, between-subject standardized mean differences $\left(\mathrm{SMD}=\frac{\text{Difference in mean outcome between groups}}{\text{Pooled standard deviation of outcome among participants}}\right)$ were calculated. SMDs were adjusted for small sample sizes by using the following factor $\left(1-\frac{3}{4N-9}\right)$ [41] with N representing the total sample size. Quantitative data synthesis for meta-analysis was accomplished by utilizing Review Manager V.5.3.5 [42]. A random effects model was applied to weight each included study according to the magnitude of its standard error and to calculate the weighted mean SMD ($\mathrm{SMD}_{\mathrm{wm}}$). At least two BT intervention groups had to be included to calculate $\mathrm{SMD}_{\mathrm{wm}}$ for balance performance outcomes. Improvement in balance performance through BT is depicted by an increase (positive) or decrease (negative) in the respective outcome parameter (i.e., CoP path length vs. time in single leg stance). Therefore, all positive effects were represented as positive $\mathrm{SMD}_{\mathrm{wm}}$ for reasons of improved readability. In addition, the calculation of $\mathrm{SMD}_{\mathrm{wm}}$ allows comparison and evaluation of BT effects in a large number of studies on different measures of balance performance. Moreover, it helps to elucidate if differences are of practical relevance.

Subgroup univariate analyses for moderator variables (i.e., chronological age, sex, training status, sport discipline, and testing methods) and training modalities (i.e., training period, training frequency, total number of training sessions, duration of training sessions, and total duration of training per week) were conducted using Review Manager V.5.3.5 by computing a weight for each subgroup [43]. Thus, SMD_{wm} values for specific sub-groups were aggregated and subgroup effect sizes were compared for statistical differences using a χ^2 trend test. This test was implemented in Review Manager. Further, a multivariate random effects meta-regression was computed with Comprehensive Meta-analysis version 3.3.70 (Biostat Inc., NJ, USA) to verify if any of the examined training modalities predict the effectiveness of BT in youth. To specify dose-response relationships, subgroups with the highest effect size magnitude (SMD_{wm}) within each training modality were utilized. According to Cohen [44], effect size values of $SMD/SMD_{wm} < 0.20$ indicate trivial, $0.20 \leq SMD/SMD_{wm} < 0.50$ indicate small, $0.50 \leq SMD/SMD_{wm} < 0.80$ indicate medium and $SMD/SMD_{wm} \geq 0.80$ indicate large effects. Between-study heterogeneity was assessed using I^2 and χ^2 statistics. As stated by Higgins et al. [45], I^2 values of 25%, 50%, and 75% were considered as low, moderate, and high heterogeneity, respectively. I^2 values above 75% were rated as considerable heterogeneity [46]. The level of significance was set at $p < 0.05$.

3 Results

3.1 Study Characteristics

The initial literature search identified 198 potentially relevant studies. One hundred and eighty one articles were found in the electronic databases and 17 articles through other sources (i.e., reference lists of relevant papers and reviews, manual search of keywords via internet). After the screening of abstracts and the analysis of full text eligibility, 17 studies remained and were included for our quantitative analysis. The procedure is displayed in a flow chart (Figure 1).

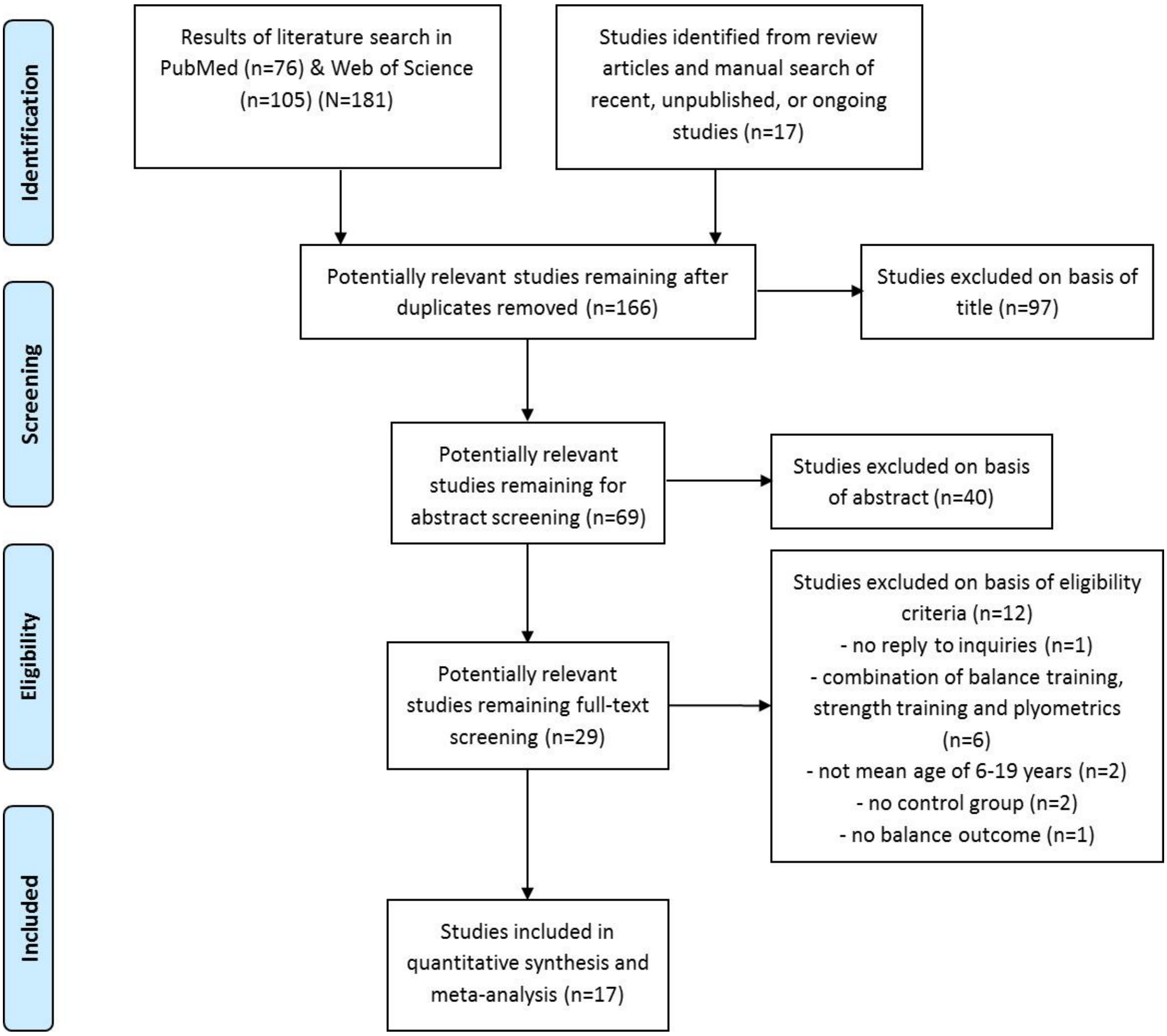


Fig. 3 Flow chart illustrating the search and selection process of the systematic literature search.

All included studies were characterized and described in Table 2. A total of 833 children and adolescents participated in the included studies and 436 received BT in 20 treatment groups. Sample sizes of intervention groups ranged from 10 to 60 participants with an age range of 6 to 19 years. In general, the duration of BT varied from 4 to 12 weeks with a mean value of 7 weeks. The study by Malliou et al. [20] was conducted over the period of a complete soccer season without further specification of the time duration. Training frequency ranged from 2 to 7 sessions per week. In the study by Kollmitzer et al. [47] subjects had to participate in 3 training sessions daily for 4 minutes each. Overall, median training frequency amounted to 3 sessions per week. Total number of training sessions ranged from 12 to 84 sessions with an average of 29 sessions. The duration of a single training session lasted 4 to 120 minutes (mean 31 minutes) and between 20 and 240 minutes per week (mean 93 minutes). BT protocols incorporated static and dynamic balance exercises in bi- and unipedal stance on stable and unstable surfaces (i.e., balance/wobble boards, BOSU© ball, DynaDisc©, foam mats), balance systems (i.e., Biodex Balance System), additional motor tasks (i.e., arm movements, passing a ball) during balance exercise as well as manipulation of sensory input (i.e., eyes open/closed). Progression of the BT protocol in terms of increasing exercise difficulty was reported in 6 out of 17 studies [19, 47-51]. More detailed information on BT protocols regarding training volume (i.e., number of exercises, number of sets, and duration of exercises) was scarce and only reported in a few studies. Further, 13 studies [18, 19, 47-57] with 15 intervention groups used test methods to assess proxies of static balance to document performance enhancing effects of BT. Twelve studies [19, 20, 47, 48, 50, 53, 54, 56-60] with 15 intervention groups used dynamic balance tests that included proactive balance and quasi-dynamic balance. Eight authors were contacted for further information, seven contributed additional information and two provided original data.

3.2 Methodological Quality of the Included Trials

In terms of quality assessment, a median PEDro score of 6 [95% confidence interval (CI) 5 to 6] indicated a moderate methodological quality of the included studies. Nine out of 17 studies reached the preassigned cut-off score of 6 on the PEDro scale (Table 3). The risk of bias across studies in terms of publication bias was checked by visual inspection of the funnel plots. Funnel plots showed no asymmetries.

3.3 Effects of Balance Training

Thirteen studies (15 intervention groups) examined the effects of BT on proxies of static balance and 12 (15 intervention groups) the effects of BT on proxies of dynamic balance compared to a passive or active control group. Figures 2 and 3 illustrate the effects of BT on measures of static and dynamic balance. The analysis revealed a SMD_{wm} of 0.71 (95% CI 0.42 to 1.01, $I^2 = 66\%$, $\chi^2 = 41.69$, $df = 14$, $p < 0.001$) for static balance indicating a moderate effect in favour of BT. The SMD_{wm} of 1.03 (95% CI 0.60 to 1.46, $I^2 = 83\%$, $\chi^2 = 80.56$, $df = 14$, $p < 0.001$) for dynamic balance was indicative of a large BT effect.

Table 3 Studies examining the effects of balance training on measures of static and dynamic balance in youth

References	No. of subjects (sex); age (mean ± SD, or range); sport; training status	Groups/training devices	Training modality No. of training weeks/frequency/sessions; No. of sets/reps/duration per exercise; single session duration; total duration per week	Exercises	Test modality; Static/dynamic balance	Results
Altinkök [53]	60 (N/A); 6 yrs; physical education; N	BAL (n=30): Activity education with coordination CON (n=30): regular activity education	8 wk / 2d / 16 sessions, N/A, 120 min; 240 min	Activity education with coordination including activities/games intended to develop motoric features	Static: Flamingo balance test, longest time interval standing in balance on one leg within one minute	BAL-pp: 40.1% ($SMD_w = 0.70$) CON-pp: -3.1% ($SMD_w = -0.05$) BAL-CON: $SMD_b = 1.07$ (95% CI = 0.53; 1.61)
					Dynamic: Stabilometer balance test; time standing in balance on the stabilometer within 30 s	BAL-pp: 32.5% ($SMD_w = 2.10$) CON-pp: 0.9% ($SMD_w = 0.06$) BAL-CON: $SMD_b = 3.19$ (95% CI = 2.41; 3.97)
Bal [48]	40 (F); 15.52 ± 1.7 yrs; volleyball; N	BAL I (*n* = 20): high volume balance training BAL II (*n* = 20): low volume balance training	6 wk / 3d / 18 sessions; BAL I: 2-4 sets of 8-15 reps or 18-35 s, BAL II: 2-4 sets of 9-13 reps or 18-30 s; 40 min; 120 min	Single leg stance, squat, hip hike; controlled inversion/eversion, plantar flexion/dorsiflexion; 4-point star, all exercises performed on Dura Disc	Static: Timed one-legged stance with eyes opened and on firm ground (Standing Stork Test)	BAL I-pp: 9.1% ($SMD_w = 0.92$) BAL II-pp: 3.5% ($SMD_w = 0.32$) BAL I-BAL II: $SMD_b = 2.36$ (95% CI = 1.54; 3.19)
					Dynamic: one-legged stance with eyes opened on a wobble board (time off balance)	BAL I-pp: 10.0% ($SMD_w = 0.80$) BAL II-pp: 4.1% ($SMD_w = 0.36$) BAL I-BAL II: $SMD_b = 0.89$ (95% CI = 0.24; 1.54)
Boccolini et al. [58]	23 (F); 15 ± 0 yrs (BAL); 14.6 ± 0.35 yrs (CON); basketball; A	BAL (*n* = 11): balance training CON (*n* = 12): isotonic training	12 wk / 2d / 24 sessions; 6-10 sets of 20 reps or 30 s; 30 min; 60 min	Kneeling on Swiss Ball, two-handed chest pass while standing on Trial-T1 half-sphere, single-leg balance on Trial-T1 half-sphere alternating the supporting leg	Dynamic: one-legged stance (right) with eyes opened and on Libra Board	BAL-pp: 41.7% ($SMD_w = 4.76$) CON-pp: 14.4% ($SMD_w = 0.80$) BAL-CON: $SMD_b = 2.60$ (95% CI = 1.44; 3.76)

Dobrijevic et al. [49]	60 (60 F); 7-8 yrs; gymnastics; N	BAL (*n*=33): BT program before rhythmic gymnastics training CON (*n*=27) regular rhythmic gymnastics training	12 wk / 2d / 24 sessions, 3 exercises with 3 sets of 30 s, 10 min; 20 min	Different tasks in uni- and bipedal stance with open and closed eyes on unstable devices (T-board, half-globe board, Pilates balls, balance beam, soft mattresses) with reduced base of support, additional tasks (balancing a ball, spinning a hoop)	Static: One-legged stance (dominant leg) on an balance beam with eyes opened (time in s)	BAL-pp: 67.2% (SMD_w = 0.97) CON-pp: 30.1% (SMD_w = 0.50) BAL-CON: SMD_b = 0.70 (95% CI = 0.18; 1.23)
Emery et al. [19]	120 (60 F, 60 M); BAL 15.9 ± 1.16 yrs; CON 15.8 ± 1.16 yrs; physical education; N	BAL (*n* = 60): home-based balance training with biweekly supervision and progression CON (*n* = 60): no intervention	6 wk / 7d / 42 sessions + 6 months / 24 sessions; N/A; 20 min.	Bipedal exercises on wobble board with open and closed eyes; Progression from bipedal to unipedal exercise and increased duration of eye-closed elements after week 2, wobble board adjustment to level 2 after week 4	Static: Timed one-legged stance with eyes closed on firm ground Dynamic: Timed one-legged stance with eyes closed on foam ground	BAL-pp: 69.5% (SMD_w = .73) CON-pp: -19.0% (SMD_w = -0.19) BAL-CON: SMD_b = 0.54 (95% CI = 0.17; 0.90) BAL-pp: 54.5% (SMD_w = 1.00) CON-pp: 13.6% (SMD_w = 0.25) BAL-CON: SMD_b = 0.38 (95% CI = 0.02; 0.74)

Gioftsidou et al. [59]	39 (M); 16 ± 1 yrs; soccer; A	BAL I (*n* = 13): BT before regular soccer training BAL II (*n* = 13): BT after regular soccer training CON (*n* = 13): regular soccer training	12 wk / 3d / 36 sessions; 5 exercises per session; N/A; 20 min; 60 min	Exercises performed on the Biodex Stability System: moving a cursor depicting the position of the centre of foot pressure to a specific target on a screen for 45 s, maintaining single-limb stance on 3 different boards with increasing instability, maintaining single-limb stance on a mini trampoline	Dynamic: 20-s one-legged stance with eyes open on a Biodex balance platform set freely to move	BAL I-pp: 35.1% (SMD_w = 0.75) BAL II-pp: 32.9% (SMD_w = 0.92) CON-pp: 1.3% (SMD_w = -0.04) BAL I-BAL II: SMD_b = -0.05 (95% CI = -0.82; 0.72) BAL I-CON: SMD_b = 1.13 (95% CI = 0.29; 1.97) BAL II-CON: SMD_b = 1.18 (95% CI = 0.33; 2.02)
Granacher et al. [18]	20 (6 F, 14 M); BAL 19 ± 1.5 yrs; CON 18 ± 1.2 yrs; physical education; N	BAL (*n* = 10; 3 F, 7 M): balance training integrated in PE class CON (*n* = 10; 3 F, 7 M): regular PE class	4 wk / 3d / 12 sessions; 4 sets of each exercise lasting 20 s; 30 min; 90 min	Two- and one-legged stance performed barefoot with eyes open and hands resting on the hips on 4 unstable devices (soft mats, ankle disks, balance boards, air cushions)	Static: 40-s one-legged (dominant leg) on a force platform, CoP displacement in ML direction in cm	BAL-pp: 17.7% (SMD_w = 0.45) CON-pp: 6.9% (SMD_w = 0.15) BAL-CON: SMD_b = 0.81 (95% CI = -0.11; 1.73)
Granacher et al. [60]	30 (16 F, 14 M); 6.6 ± 0.5 yrs (BAL); 6.5 ± 0.5 yrs (CON); physical education; N	BAL (*n* = 15): BT program integrated into regular PE lessons CON (*n* = 15): regular PE lessons	4 wk / 3d /12 sessions; 4 sets of 20 s; 45 min; 135 min	Two- and one-legged stance on unstable devices (soft mats, ankle disks, balance boards, air cushions) with reduced base of support, additional arm movements, manipulated sensory input	Dynamic: 20-s two-legged stance with eyes opened and on swing platform with foam ground (total CoP displacement in mm)	BAL-pp: 7.3% (SMD_w = 0.15) CON-pp: 4.7% (SMD_w = 0.19) BAL-CON: SMD_b = -0.09 (95% CI = -0.8; 0.63)

Heleno et al. [54]	22 (22 M); BAL 14.9 ± 0.8 yrs; CON 15.2 ± 0.8 yrs; soccer; A	BAL (n = 12): balance training additional to regular soccer training CON (n = 10): regular soccer training	5 wk / 3d / 15 sessions; 50 min; 150 min	Static postural control and jumping exercises were performed single-legged with closed and opened eyes on stable and unstable ground, weekly progression in difficulty of the exercises	Static: 30-s single-legged stance on the dominant leg with eyes open on firm ground on a force platform (CoP area of sway in cm²)	BAL-pp: 11.3% (*SMD*$_w$ = 0.32) CON-pp: -6.9% (*SMD*$_w$ = -0.20) BAL-CON: *SMD*$_b$ = 0.32 (95% CI = -0.61; 1.07)
					Dynamic: modified Star Excursion Balance Test (in %)	BAL-pp: 3.8% (*SMD*$_w$ = 0.56) CON-pp: -2.6% (*SMD*$_w$ = -0.45) BAL-CON: *SMD*$_b$ = -0.23 (95% CI = -1.08; 0.61)
Kayapmar [52]	80 (40 F, 40 M); 5-7 yrs; physical education; N	BAL (n = 40): movement education with balance exercises CON (n = 40): no intervention	12 wk / 3d / 36 sessions; N/A; 25 min.; N/A	Posture exercises (no further specification), basic motor exercises (no further specification) and games incorporating skills learned through posture and basic motor exercises	Static: one-legged stance with eyes opened on a balance beam (time in s)	BAL-pp:61.6% (*SMD*$_w$ = 0.67) CON-pp:-6.2% (*SMD*$_w$ = -0.07) BAL-CON: *SMD*$_b$ = 1.00 (95% CI = 0.53;1.46)
Kollmitzer et al. [47]	26 (3 F, 23 M); 16-17 yrs; physical education; N	BAL (n = 13): balance training CON (n = 13): strength training	4 wk / 7d and 3 times daily / 84 sessions; 4 min; 84 min	Subjects trained their balance skills on a wobbling feedback platform	Static: 20-s two-legged stance with eyes opened and on firm ground on a force plate	BAL-pp: 10.4% (*SMD*$_w$ = 0.29) CON-pp: -8.8% (*SMD*$_w$ = -0.36) BAL-CON: *SMD*$_b$ = 0.59 (95% CI = -0.20; 1.38)
					Dynamic: standing on a wobbling feedback platform and directing a ball during 30 s as frequently as possible through a labyrinth integrated in the stance plane by voluntarily changing tilt and obliquity of the platform	BAL-pp: 254% (*SMD*$_w$ =2.70) CON-pp: 5.8% (*SMD*$_w$ = 0.08) BAL-CON: *SMD*$_b$ = 1.35 (95% CI = 0.48; 2.21)

Kovacs et al. [50]	45 (N/A); 18.5 ± 3 yrs; ice-skating; A	BAL (n = 22) off-ice balance training CON (n = 23) basic off-ice training	4 wk / 3d / 12 sessions; 25 min; 75 min	Single-limb exercises on different wobble boards, mini trampoline and with open and closed eyes; sport-specific exercises, including landing and spinning exercises	Static: 15-s one-legged stance with eyes opened on a force platform (total CoP displacement in cm)	BAL-pp: 5.4% (SMD_{w} = 0.32) CON-pp: -1.7% (SMD_{w} = -0.09) BAL-CON: SMD_{b} = 0.42 (95% CI = -0.18; 1.02)
					Dynamic: 15-s in single-limb stance with skate on and eyes opened on a force platform (total CoP displacement in cm)	BAL-pp: 18.1% (SMD_{w} = 0.92) CON-pp: 3.6% (SMD_{w} = 0.12) BAL-CON: SMD_{b} = 0.39 (95% CI = -0.21; 0.99)
Ljubojevic et al. [51]	38 (N/A); 15-19 yrs; dancing; A	BAL (n = 19) regular dance training with additional balance exercises CON (n = 19) regular dance training	12 wk / 3d / 36 session; 30 min; 90 min	Balance exercises performed on various unstable surfaces (i.e., moving roller, T-board, semi-roller, ”Bosu” ball) under alternating conditions (i.e. eyes open/closed, with distraction, dual task)	Static: Flamingo balance test; longest time interval standing in balance on one leg within one minute	BAL-pp: 31.9% (SMD_{w} = 2.17) CON-pp: 0.1% (SMD_{w} = 0.01) BAL-CON: SMD_{b} = 1.72 (95% CI = 0.96; 2.47)
Malliou et al. [20]	100 (N/A); BAL 16.7 ± 0.5 yrs; CON 16.9 ± 0.7 yrs; soccer; A	BAL (*n* = 50): regular soccer training and balance training CON (*n* = 50): regular soccer training only	During competition period (2001-2002) / 2d / N/A; 20 min; 40 min	Balance exercises performed on the Biodex Stability System, mini trampoline, and balance boards. Soccer players attempted to maintain balance while they were performing soccer agilities.	Dynamic: 20s one-legged stance with eyes opened dynamic ground (i.e., Biodex Stability System)	BAL-pp: 37.0% (SMD_{w} = 0.86) CON-pp: 1.3% (SMD_{w} = 0.03) BAL-CON: SMD_{b} = 1.02 (95% CI = 0.60; 1.44)
Pau et al. [55]	26 (F); BAL 13.2 ± 0.7 yrs; CON 13.0 ± 0.4 yrs; volleyball; N	BAL (*n* = 13): regular volleyball training and balance training CON (*n* = 13): regular volleyball training only	6 wk / 3d / 18 sessions; 25 min; 75 min	Walking tasks; two- and one-legged stance	Static: 10-s one-legged stance with the dominant leg on firm ground and eyes opened	BAL-pp: 1.4% (SMD_{w} = 0.04) CON-pp: 17.6% (SMD_{w} = 0.75) BAL-CON: SMD_{b} = -0.44 (95% CI = -1.21; 0.34)

Wälchli et al. [56]	77 (38 F; 39 M); BAL I 6.2 ± 0.4 yrs; CON I 6.2 ± 0.8 yrs; BAL II 11.4 ± 0.5 yrs; CON II 11.4 ± 0.7 yrs; BAL III 14.1 ± 0.5 yrs; CON II 14.9 ± 0.8 yrs	BAL I-III: physical education lessons with child-oriented balance training; BAL I (*n* = 15); BAL II (*n* = 18); BAL III(*n* = 15) CON I-III: regular physical education lessons; CON I (*n* = 10); CON II (*n* = 9); CON III (*n* = 10)	5 wk / 2d / 10 sessions; 45 min; 90 min	Child-oriented balance training consisting of three different topics (i.e., balance circuit, two Parkour lessons, and competitive balance games)	Static: 15-s one legged stance with the right leg on a Pedalo-Pro-Pedes training device with eyes open	BAL I-pp: 28.8% (SMD_w = 4.91) CON I-pp: -6.0% (SMD_w = -0.83) BAL I-CON I: SMD_b = 0.72 (95% CI = -0.11; 1.55); BAL II-pp: 13.5% (SMD_w = 2.30) CON II-pp: 1.8% (SMD_w = 0.24) BAL II-CON II: SMD_b = -0.59 (95% CI = -0.23; 1.41); BAL III-pp: 8.4% (SMD_w = 1.14) CON III-pp: 5.3% (SMD_w = 0.88) BAL III-CON III: SMD_b = -0.19 (95% CI = -0.99; 0.61)
					Dynamic: 15-s one legged stance with the right leg on a PosturoMed-System with eyes open	BAL I-pp: 54.7% (SMD_w = 6.80) CON I-pp: 21.1% (SMD_w = 1.74) BAL I-CON I: SMD_b = 1.75 (95% CI = 0.79; 2.71); BAL II-pp: 21.8% (SMD_w = 1.86) CON II-pp: 34.7% (SMD_w = 2.46) BAL II-CON II: SMD_b = -0.05 (95% CI = -0.85; 0.76); BAL III-pp: 27.9% (SMD_w = 2.12) CON III-pp: 31.2% (SMD_w = 2.87) BAL III-CON III: SMD_b = 1.90 (95% CI = -0.01; 1.55)
Winter et al. [57]	28 (11 F, 17 M); BAL 12.6 ± 1.5 yrs; CON 12.9 ± 1.7 yrs; speed/ice skating; A	BAL (*n* =14; 6 F, 8 M); regular speed skating training and balance training CON (*n* = 14; 5 F, 9 M); regular speed skating training	12 wk / 5d / 60 sessions; 2 sets of 6 exercises with a duration of 45 s and 30 s rest period; 15 min; 75 min	Strengthening exercises with 45-cm clubs on an Airex Balance Board; Joint position exercises with an angle board; balance exercises on a wobble board and Pedalo	Static: 20-s one legged stance (right) on a force platform with eyes open	BAL-pp: 5.0% (SMD_w = 0.28) CON-pp: -0.4% (SMD_w = -0.03) BAL-CON: SMD_b = 0.53 (95% CI = -0.23; 1.29)
					Dynamic: 20s one-legged stance (right) with eyes opened	BAL-pp: 49.9% (SMD_w = 0.98) CON-pp: -23.7% (SMD_w = -0.94)

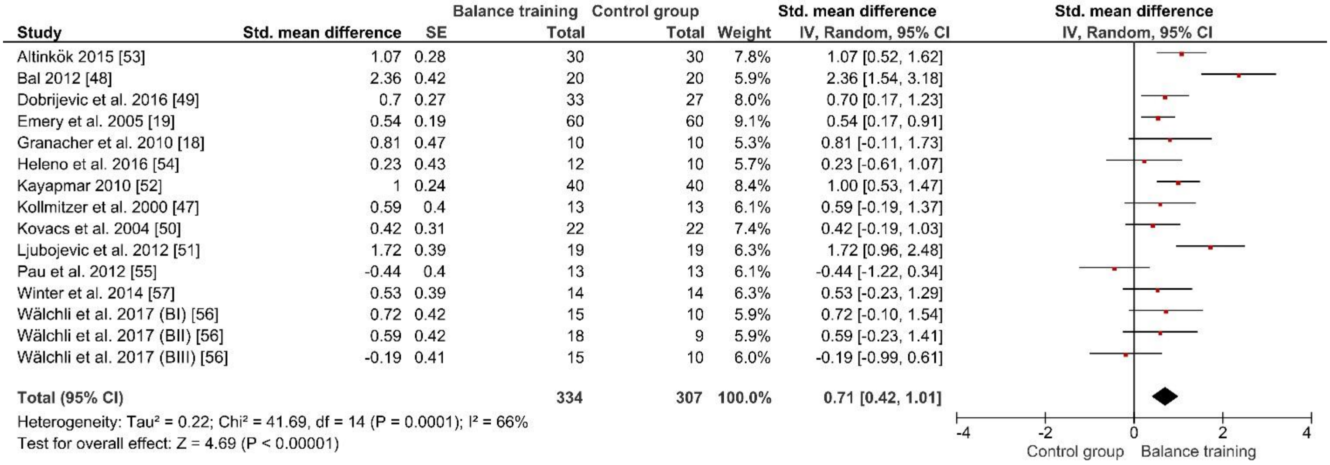
	round woods	dynamic ground (i.e., Biodex Stability System; Level 2)	BAL-CON: SMD_b = 0.78 (95% CI = 0.01; 1.55)

A athletes, *BAL* balance training group, *BT* balance training; *CI* confidence interval, *CON* control group, *CoP* centre of pressure, *d* days per week, *F* female, *M* male, *min* minutes, *ML* medio-lateral; *N* non-athletes, *N/A* not available, *PE* physical education; *pp* pre-post; *reps* repetitions, *s* seconds, SMD_b standardized mean difference between groups, SMD_w standardized mean difference within groups, *wk* weeks, *yrs* years

Table 4 Physiotherapy Evidence Database (PEDro) scores of the reviewed studies

Authors	Eligibility criteria[a]	Randomized assignation	Blinded assignation	Group homogeneity	Blinded subjects	Blinded coaches	Blinded investigator	Dropout < 15%	Intention-to-treat	Group comparisons	Point and variability measures	Total PEDro score
Altinkök [53]	+	-	-	-	-	-	-	+	+	+	+	4
Bal [48]	-	+	-	-	-	-	-	+	+	+	+	5
Boccolini et al. [58]	+	+	-	+	-	-	-	+	+	+	+	6
Dobrijevic et al. [49]	-	+	-	+	-	-	-	+	+	+	+	6
Emery et al. [19]	+	+	-	+	-	-	-	+	+	+	+	6
Gioftsidou et al. [59]	+	+	-	-	-	-	-	+	+	+	+	5
Granacher et al. [18]	+	+	-	+	-	-	-	+	+	+	+	6
Granacher et al. [60]	+	+	-	+	-	-	-	+	+	+	+	6
Heleno et al. [54]	+	+	+	+	-	-	+	+	+	+	+	8
Kayapmar [52]	+	+	-	+	-	-	-	+	+	+	+	5
Kollmitzer et al. [47]	+	+	-	+	-	-	-	+	+	+	+	6
Kovacs et al. [50]	+	+	+	+	-	-	-	+	+	+	+	7
Ljubojevic et al. [51]	-	-	-	+	-	-	-	+	+	+	+	5
Malliou et al. [20]	-	+	-	+	-	-	-	+	+	+	+	6
Pau et al. [55]	-	-	-	-	-	-	-	+	+	+	+	4
Wälchli et al. [56]	+	-	-	+	-	-	-	+	+	+	+	5
Winter et al. [57]	+	+	-	-	-	-	-	+	+	+	+	5

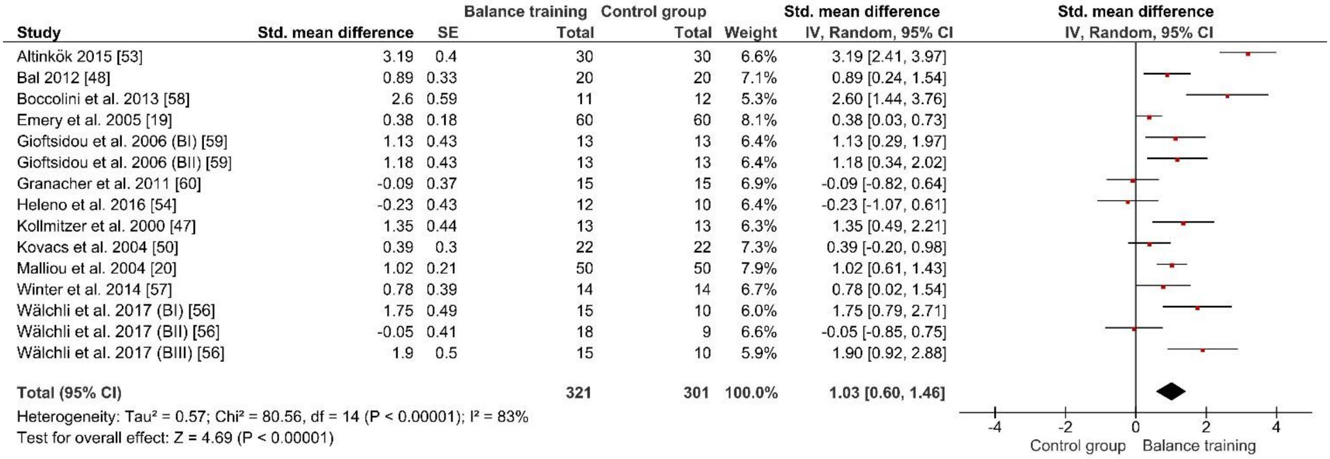
[a] The eligibility criteria has to be excluded for calculation of the total PEDro score. “+” = indicates a ‘‘yes’’ score; “–“ = indicates a ‘‘no’’ score



Study	Std. mean difference	SE	Balance training Total	Control group Total	Weight	Std. mean difference IV, Random, 95% CI
Altinkök 2015 [53]	1.07	0.28	30	30	7.8%	1.07 [0.52, 1.62]
Bal 2012 [48]	2.36	0.42	20	20	5.9%	2.36 [1.54, 3.18]
Dobrijevic et al. 2016 [49]	0.7	0.27	33	27	8.0%	0.70 [0.17, 1.23]
Emery et al. 2005 [19]	0.54	0.19	60	60	9.1%	0.54 [0.17, 0.91]
Granacher et al. 2010 [18]	0.81	0.47	10	10	5.3%	0.81 [-0.11, 1.73]
Heleno et al. 2016 [54]	0.23	0.43	12	10	5.7%	0.23 [-0.61, 1.07]
Kayapmar 2010 [52]	1	0.24	40	40	8.4%	1.00 [0.53, 1.47]
Kollmitzer et al. 2000 [47]	0.59	0.4	13	13	6.1%	0.59 [-0.19, 1.37]
Kovacs et al. 2004 [50]	0.42	0.31	22	22	7.4%	0.42 [-0.19, 1.03]
Ljubojevic et al. 2012 [51]	1.72	0.39	19	19	6.3%	1.72 [0.96, 2.48]
Pau et al. 2012 [55]	-0.44	0.4	13	13	6.1%	-0.44 [-1.22, 0.34]
Winter et al. 2014 [57]	0.53	0.39	14	14	6.3%	0.53 [-0.23, 1.29]
Wälchli et al. 2017 (BI) [56]	0.72	0.42	15	10	5.9%	0.72 [-0.10, 1.54]
Wälchli et al. 2017 (BII) [56]	0.59	0.42	18	9	5.9%	0.59 [-0.23, 1.41]
Wälchli et al. 2017 (BIII) [56]	-0.19	0.41	15	10	6.0%	-0.19 [-0.99, 0.61]
Total (95% CI)			**334**	**307**	**100.0%**	**0.71 [0.42, 1.01]**

Heterogeneity: Tau² = 0.22; Chi² = 41.69, df = 14 (P = 0.0001); I² = 66%
Test for overall effect: Z = 4.69 (P < 0.00001)

Fig. 4 Effects of balance training (experimental) vs. control on measures of static balance in youth; *BI* balance training group I*; BII* balance training group II*; BIII* balance training group III; *CI* confidence interval, *IV* inverse variance, *SE* standard error; *Std.* Standardized



Study	Std. mean difference	SE	Balance training Total	Control group Total	Weight	Std. mean difference IV, Random, 95% CI
Altinkök 2015 [53]	3.19	0.4	30	30	6.6%	3.19 [2.41, 3.97]
Bal 2012 [48]	0.89	0.33	20	20	7.1%	0.89 [0.24, 1.54]
Boccolini et al. 2013 [58]	2.6	0.59	11	12	5.3%	2.60 [1.44, 3.76]
Emery et al. 2005 [19]	0.38	0.18	60	60	8.1%	0.38 [0.03, 0.73]
Gioftsidou et al. 2006 (BI) [59]	1.13	0.43	13	13	6.4%	1.13 [0.29, 1.97]
Gioftsidou et al. 2006 (BII) [59]	1.18	0.43	13	13	6.4%	1.18 [0.34, 2.02]
Granacher et al. 2011 [60]	-0.09	0.37	15	15	6.9%	-0.09 [-0.82, 0.64]
Heleno et al. 2016 [54]	-0.23	0.43	12	10	6.4%	-0.23 [-1.07, 0.61]
Kollmitzer et al. 2000 [47]	1.35	0.44	13	13	6.3%	1.35 [0.49, 2.21]
Kovacs et al. 2004 [50]	0.39	0.3	22	22	7.3%	0.39 [-0.20, 0.98]
Malliou et al. 2004 [20]	1.02	0.21	50	50	7.9%	1.02 [0.61, 1.43]
Winter et al. 2014 [57]	0.78	0.39	14	14	6.7%	0.78 [0.02, 1.54]
Wälchli et al. 2017 (BI) [56]	1.75	0.49	15	10	6.0%	1.75 [0.79, 2.71]
Wälchli et al. 2017 (BII) [56]	-0.05	0.41	18	9	6.6%	-0.05 [-0.85, 0.75]
Wälchli et al. 2017 (BIII) [56]	1.9	0.5	15	10	5.9%	1.90 [0.92, 2.88]
Total (95% CI)			**321**	**301**	**100.0%**	**1.03 [0.60, 1.46]**

Heterogeneity: Tau² = 0.57; Chi² = 80.56, df = 14 (P < 0.00001); I² = 83%
Test for overall effect: Z = 4.69 (P < 0.00001)

Fig. 5 Effects of balance training (experimental) vs. control on measures of dynamic balance in youth; *BI* balance training group I*; BII* balance training group II*; BIII* balance training group III; *CI* confidence interval, *IV* inverse variance, *SE* standard error; *Std.* Standardized

3.4 Moderators of Balance Performance: Effects of Chronological Age, Sex, Training status, Setting, and Testing Methods

Subgroup analyses regarding chronological age, sex, training status, setting, and testing method were conducted to elucidate moderating effects of these variables on overall balance performance. The analyses revealed no statistically significant effect on proxies of overall balance irrespective of the moderator variable. However, subgroup analysis identified a considerable heterogeneity for the following subgroups: children (I^2 = 90%), nonathletes (I^2 = 86%), school (I^2 = 87%), and physical fitness tests (I^2 = 89%). An overview of the findings from our sub-analyses is presented in Table 4.

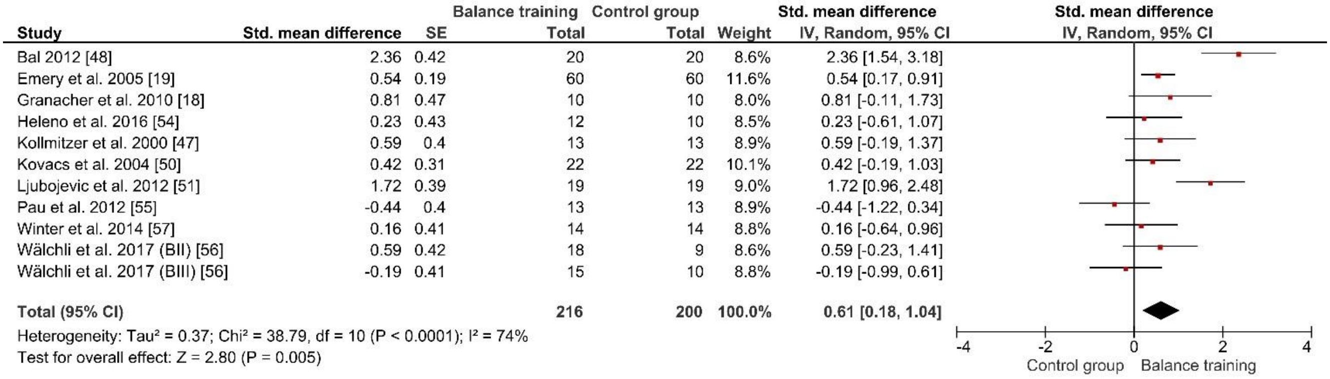
Table 5 Results of the overall balance subgroup analyses on the influence of moderator variables age, sex, training status, setting, and testing method on balance training in youth

Independent variables	SMD_{wm}	95% CI	I^2 (%)	df	χ^2 value and (p) between groups
Age					
Children (F: 5-7 yrs; M: 5-9 yrs)	1.28	0.34 – 2.23	90	4	$\chi^2 = 0.75$ (p=0.39)
Adolescents (F: 8-19 yrs, M: 10-19yrs)	0.84	0.50 – 1.18	72	14	
Sex					
Boys	1.07	0.39 – 1.76	75	4	$\chi^2 =1.63$ (p=0.20)
Girls	0.42	-0.3 – 1.15	73	2	
Training status					
Trained	0.96	0.56 – 1.37	67	8	$\chi^2 = <0.00$ (p=0.97)
Untrained	0.95	0.39 – 1.50	86	10	
Setting					
Club-based sports	0.84	0.45 – 1.23	71	10	$\chi^2 = 0.51$ (p=0.48)
School-based sports	1.11	0.48 – 1.74	87	8	
Testing method					
Physical fitness tests	1.26	0.58 – 1.95	89	5	$\chi^2 = 1.25$ (p=0.26)
Biomechanical tests	0.81	0.41 – 1.21	73	13	

CI confidence interval; *df* degrees of freedom; *F* female, I^2 heterogeneity between studies, *M* male, *p* significance level, SMD_{wm} weighted mean standardized mean difference, *yrs* years

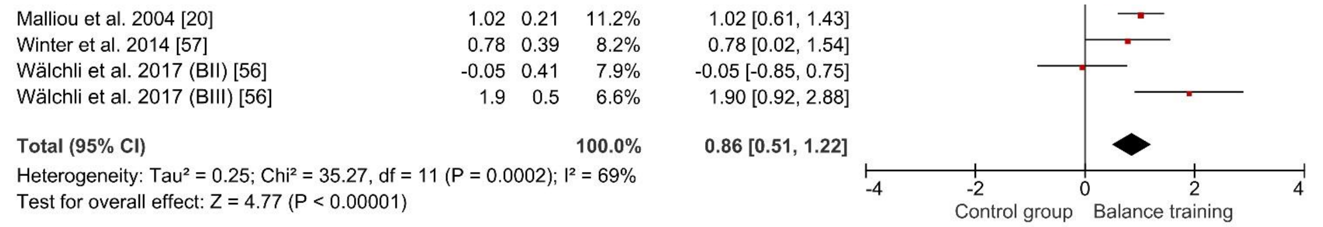
3.5 Effects and Dose-Response Relationships following Balance Training in Adolescents

We analysed effects of BT in adolescents on balance performance (i.e., static balance, dynamic balance, and overall balance) separately. This was done to lower between-study heterogeneity and only a small number of studies ($n = 5$) examined the effects of BT on balance performance in children. Ten studies (11 intervention groups) examined the effects of BT on proxies of static balance and another 10 studies (12 intervention groups) investigated the effects of BT on proxies of dynamic balance compared with a passive or active control group in youth aged 12 – 19 years. Results of 13 studies (15 intervention groups) were combined to analyse the effects of BT on overall balance. Figures 4, 5 and 6 illustrate the effects of BT on static, dynamic, and overall balance, respectively, in adolescents. The analysis revealed a moderate effect ($SMD_{wm} = 0.61$, 95% CI 0.18 to 1.04, $I^2 = 74\%$, $\chi^2 = 38.79$, $df = 10$, $p < 0.001$) of BT on static balance and a large effect ($SMD_{wm} = 0.86$, 95% CI 0.51 to 1.22, $I^2 = 69\%$, $\chi^2 = 35.27$, $df = 11$, $p < 0.001$) on dynamic balance in adolescents. A SMD_{wm} of 0.84 (95% CI 0.50 to 1.18, $I^2 = 72\%$, $\chi^2 = 50.31$, $df = 14$, $p < 0.001$) for overall balance was indicative of a large BT effect. With reference to the pooled data for overall balance, a multivariate random effects meta-regression (Table 5) was conducted to explore the influence of training modalities on the effectiveness of BT on balance performance in youth. In addition to the meta-regression, we established dose-response relationships for specific training modalities (i.e., training period, training frequency, total number of training sessions, duration of training sessions, and total duration of training per week) independently (modality-specific) via subgroup analysis using the effect size of subgroups for each training modality (Table 6). Categories of training modalities with only one study were excluded from subgroup analyses. Modality specific subgroups with the highest magnitude effect sizes are presented for the analysis of dose-response relationships. The volume related modalities 'number of exercises', 'duration of a set', 'number of repetitions', and 'duration of an exercise' had to be excluded from our dose-response quantifications due to the limited data availability. Further, we were not able to quantify dose-response relationships for exercise or training intensity as this training modality was not reported for BT.



Study	Std. mean difference	SE	Balance training Total	Control group Total	Weight	Std. mean difference IV, Random, 95% CI
Bal 2012 [48]	2.36	0.42	20	20	8.6%	2.36 [1.54, 3.18]
Emery et al. 2005 [19]	0.54	0.19	60	60	11.6%	0.54 [0.17, 0.91]
Granacher et al. 2010 [18]	0.81	0.47	10	10	8.0%	0.81 [-0.11, 1.73]
Heleno et al. 2016 [54]	0.23	0.43	12	10	8.5%	0.23 [-0.61, 1.07]
Kollmitzer et al. 2000 [47]	0.59	0.4	13	13	8.9%	0.59 [-0.19, 1.37]
Kovacs et al. 2004 [50]	0.42	0.31	22	22	10.1%	0.42 [-0.19, 1.03]
Ljubojevic et al. 2012 [51]	1.72	0.39	19	19	9.0%	1.72 [0.96, 2.48]
Pau et al. 2012 [55]	-0.44	0.4	13	13	8.9%	-0.44 [-1.22, 0.34]
Winter et al. 2014 [57]	0.16	0.41	14	14	8.8%	0.16 [-0.64, 0.96]
Wälchli et al. 2017 (BII) [56]	0.59	0.42	18	9	8.6%	0.59 [-0.23, 1.41]
Wälchli et al. 2017 (BIII) [56]	-0.19	0.41	15	10	8.8%	-0.19 [-0.99, 0.61]
Total (95% CI)			**216**	**200**	**100.0%**	**0.61 [0.18, 1.04]**

Heterogeneity: Tau² = 0.37; Chi² = 38.79, df = 10 (P < 0.0001); I² = 74%
Test for overall effect: Z = 2.80 (P = 0.005)

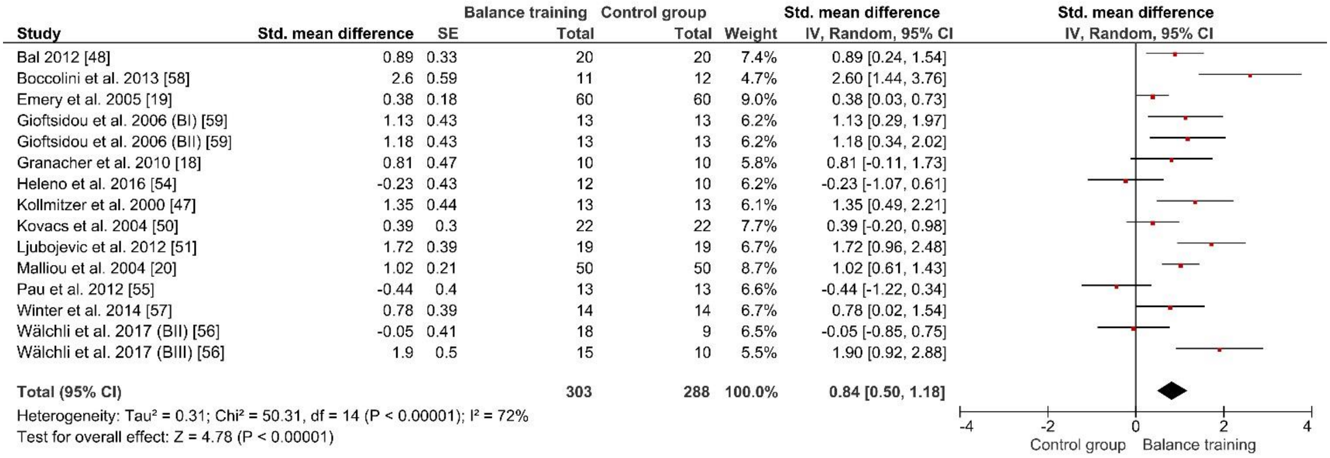


Malliou et al. 2004 [20]	1.02	0.21	11.2%	1.02 [0.61, 1.43]
Winter et al. 2014 [57]	0.78	0.39	8.2%	0.78 [0.02, 1.54]
Wälchli et al. 2017 (BII) [56]	-0.05	0.41	7.9%	-0.05 [-0.85, 0.75]
Wälchli et al. 2017 (BIII) [56]	1.9	0.5	6.6%	1.90 [0.92, 2.88]
Total (95% CI)			**100.0%**	**0.86 [0.51, 1.22]**

Heterogeneity: Tau² = 0.25; Chi² = 35.27, df = 11 (P = 0.0002); I² = 69%
Test for overall effect: Z = 4.77 (P < 0.00001)

Fig. 6 Effects of balance training (experimental) vs. control on measures of static balance in adolescence; *BII* balance training group II*; BIII* balance training group III; *CI* confidence interval, *IV* inverse variance, *SE* standard error; *Std.* Standardized

Fig. 7 Effects of balance training (experimental) vs. control on measures of dynamic balance in adolescence; *BI* balance training group I*; BII* balance training group II*; BIII* balance training group III; *CI* confidence interval, *IV* inverse variance, *SE* standard error; *Std.* Standardized



Study	Std. mean difference	SE	Balance training Total	Control group Total	Weight	Std. mean difference IV, Random, 95% CI
Bal 2012 [48]	0.89	0.33	20	20	7.4%	0.89 [0.24, 1.54]
Boccolini et al. 2013 [58]	2.6	0.59	11	12	4.7%	2.60 [1.44, 3.76]
Emery et al. 2005 [19]	0.38	0.18	60	60	9.0%	0.38 [0.03, 0.73]
Gioftsidou et al. 2006 (BI) [59]	1.13	0.43	13	13	6.2%	1.13 [0.29, 1.97]
Gioftsidou et al. 2006 (BII) [59]	1.18	0.43	13	13	6.2%	1.18 [0.34, 2.02]
Granacher et al. 2010 [18]	0.81	0.47	10	10	5.8%	0.81 [-0.11, 1.73]
Heleno et al. 2016 [54]	-0.23	0.43	12	10	6.2%	-0.23 [-1.07, 0.61]
Kollmitzer et al. 2000 [47]	1.35	0.44	13	13	6.1%	1.35 [0.49, 2.21]
Kovacs et al. 2004 [50]	0.39	0.3	22	22	7.7%	0.39 [-0.20, 0.98]
Ljubojevic et al. 2012 [51]	1.72	0.39	19	19	6.7%	1.72 [0.96, 2.48]
Malliou et al. 2004 [20]	1.02	0.21	50	50	8.7%	1.02 [0.61, 1.43]
Pau et al. 2012 [55]	-0.44	0.4	13	13	6.6%	-0.44 [-1.22, 0.34]
Winter et al. 2014 [57]	0.78	0.39	14	14	6.7%	0.78 [0.02, 1.54]
Wälchli et al. 2017 (BII) [56]	-0.05	0.41	18	9	6.5%	-0.05 [-0.85, 0.75]
Wälchli et al. 2017 (BIII) [56]	1.9	0.5	15	10	5.5%	1.90 [0.92, 2.88]
Total (95% CI)			**303**	**288**	**100.0%**	**0.84 [0.50, 1.18]**

Heterogeneity: Tau² = 0.31; Chi² = 50.31, df = 14 (P < 0.00001); I² = 72%
Test for overall effect: Z = 4.78 (P < 0.00001)

Fig. 8 Effects of balance training (experimental) vs. control on measures of overall balance in adolescence; *BI* balance training group I*; BII* balance training group II*; BIII* balance training group III; *CI* confidence interval, *IV* inverse variance, *SE* standard error; *Std.* Standardized

3.5.1 *Meta-Regression Analysis for Training Modalities of Balance Performance*

Table 5 shows the results of the multivariate random effects meta-regression for five training modalities: training period, training frequency, total number of training sessions, duration of single training sessions, and total duration of training per week. None of the training modalities predicted the effects of BT (p = 0.28 – 0.92) on overall balance performance in adolescents. Further, the multivariate meta-regression revealed an explained variance of R² = 0.00.

Table 6 Results of the multivariate random effects meta-regression analysis for training modalities of different categories to predict BT effects on overall balance performance in adolescents

Training modalities	Coefficient	Standard Error	95% CI	z-value	2-sided p-value
Training period	0.1213	0.1136	-0.1013 − 0.3439	1.07	0.28
Training frequency	0.4597	0.8455	-1.1973 − 2.1168	0.54	0.59
Number of sessions	0.0034	0.0340	-0.0633 − 0.0701	0.10	0.92
Single session duration	0.0792	0.0844	-0.0862 − 0.2446	0.94	0.35
Total duration per week	-0.0275	0.0300	-0.0863 − 0.0314	-0.92	0.36

BT balance training*; CI* confidence interval

Table 7 Results for the subgroup analyses on the effects of different categories of respective training modalities on overall balance

Independent training modality	SMD_{wm}	95% CI	z-value and (p)	I^2 (%)	df	χ^2 value and (p) between groups
Training period (weeks)						
4 weeks	0.78	0.21 – 1.35	2.66 (p = 0.008)	39	2	χ^2 = 7.28 (p = 0.06)
5 weeks	0.51	-0.74 – 1.77	0.80 (p = 0.42)	84	2	
6 weeks	0.32	-0.29 – 0.93	1.03 (p = 0.30)	70	2	
12 weeks	1.40	0.86 – 1.94	5.09 (p < 0.001)	16	4	
Training frequency						
2 sessions per week	1.29	0.35 – 2.23	2.70 (p = 0.007)	82	3	χ^2 =1.28 (p = 0.53)
3 sessions per week	0.68	0.18 – 1.17	2.69 (p = 0.007)	70	7	
7 sessions per week	0.78	-0.16 – 1.72	1.64 (p = 0.10)	76	1	
Number of sessions						
10-18 sessions	0.44	-0.09 – 0.97	1.63 (p = 0.10)	70	6	χ^2 = 8.35 (p = 0.02)
24-36 sessions	1.58	1.00 – 2.15	5.39 (p < 0.001)	41	3	
42 or more sessions	0.81	0.38 – 1.25	3.66 (p < 0.001)	61	3	
Single session duration						
4-15 min	1.03	0.46 – 1.60	3.53 (p < 0.001)	0	1	χ^2 = 0.14 (p = 0.93)
16-30 min	0.90	0.45 – 1.35	3.90 (p < 0.001)	76	8	
31-45 min	0.88	-0.11 – 1.87	1.74 (p = 0.08)	78	2	
Total duration per week						
31-60 min	1.33	0.77 – 1.89	4.68 (p < 0.001)	53	3	χ^2 = 8.20 (p = 0.02)
61-90 min	0.78	0.23 – 1.34	2.76 (p = 0.006)	74	7	
121-150 min	0.2	-0.35 – 0.75	0.72 (p = 0.47)	42	1	

df degrees of freedom*; CI* confidence interval; I^2 heterogeneity between studies; *p* level of significance; SMD_{wm} weighted mean standardized mean difference; *z-value* z-value of the test for the presence of an overall effect

3.5.2 *Training Period*

The overall dose-response relationships related to the modality ‘training period’ are illustrated in Figure 7. Training periods of 12 weeks showed the largest effect on overall balance performance. The SMD_{wm} was 1.40 (4 studies; 5 intervention groups; 95% CI 0.86 to 1.94, I^2 = 50%, χ^2 = 7.94, *df* = 4, *p* = 0.09) and was calculated from 12 studies with 14 intervention groups.

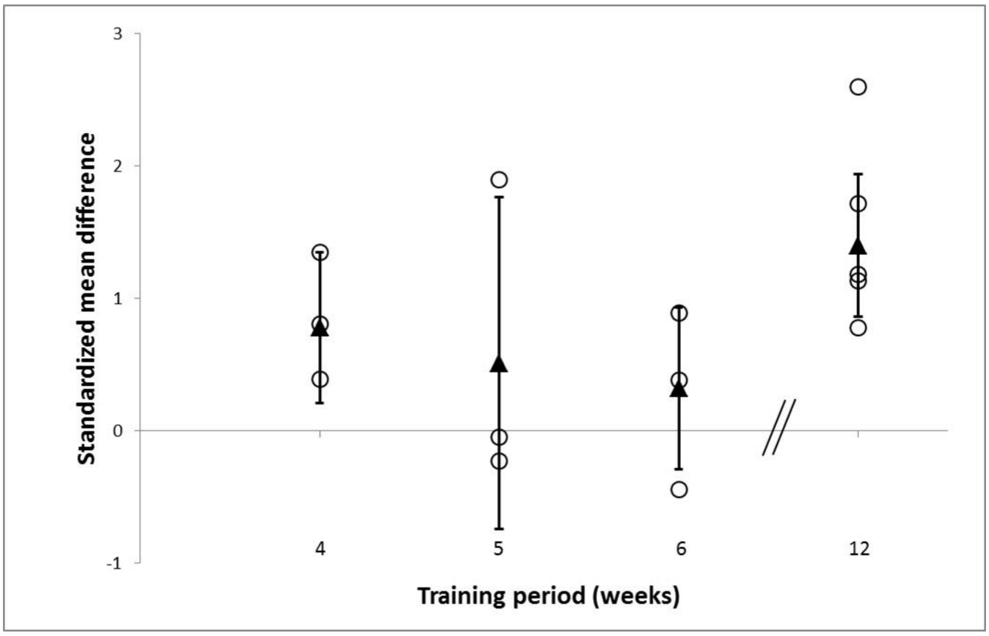


Fig. 9 Dose-response relationships of the training modality 'training period' on measures of overall balance in adolescents. Between-subject standardized mean difference (SMD) for each study is depicted by a white filled circle, whereas black triangles represent weighted mean SMD of all studies in a category

3.5.3 *Training Frequency*

The overall dose-response relationships related to the modality 'training frequency' are illustrated in Figure 8. A training frequency of two times per week showed the largest effect on overall balance performance. The SMD_{wm} amounted to 1.29 (3 studies; 4 intervention groups; 95% CI 0.35 to 2.23; $I^2 = 82\%$, $\chi^2 = 17.00$, $df = 3$, $p < 0.001$) and was calculated from 12 studies with 14 intervention groups.

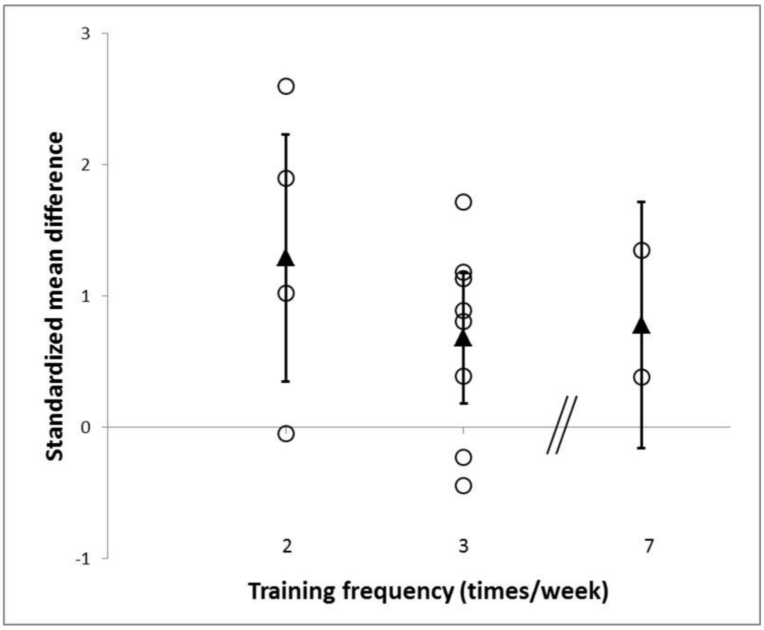


Fig. 10 Dose-response relationships of the training modality 'training frequency' on measures of overall balance in adolescents. Between-subject standardized mean difference (SMD) for each study is depicted by a white filled circle, whereas black triangles represent weighted mean SMD of all studies in a category

3.5.4 *Total Number of Training Sessions*

The overall dose-response relationships related to the volume specific modality ‘total number of training sessions’ are shown in Figure 9. A total of 24-36 sessions during intervention showed the largest effect on overall balance performance. The SMD_{wm} was calculated to be 1.58 (3 studies; 4 interventions groups; 95% CI 1.00 to 2.15; $I^2 = 41\%$, $\chi^2 = 5.05$, $df = 3$, $p = 0.17$) from 13 studies with 15 intervention groups.

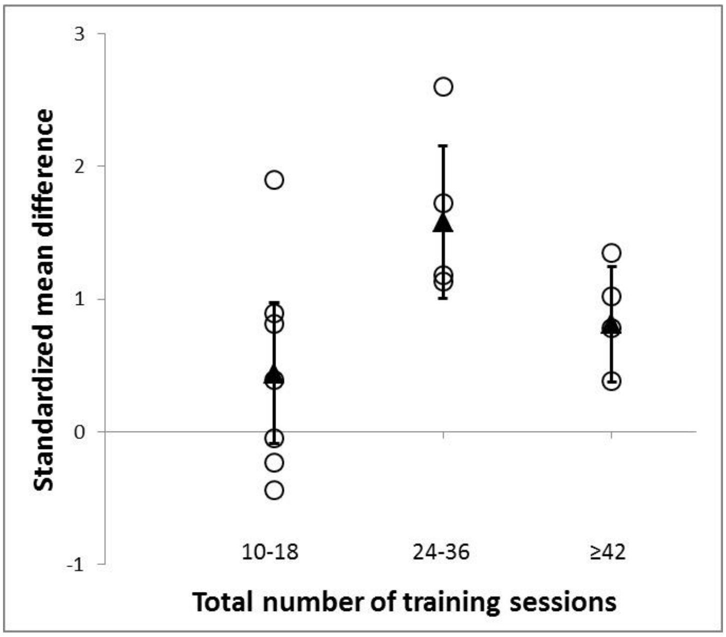


Fig. 11 Dose-response relationships of the training modality ‘total number of training sessions’ on measures of overall balance in adolescents. Between-subject standardized mean difference (SMD) for each study is depicted by a white filled circle, whereas black triangles represent weighted mean SMD of all studies in a category

3.5.5 *Duration of Training Sessions*

The overall dose-response relationships related to the volume specific modality of ‘duration of a training session’ are depicted in Figure 10. A duration of 4-15 minutes per training session showed the largest effect on overall balance performance. The SMD_{wm} from 12 studies with 14 intervention groups amounted to 1.03 (2 studies; 95% CI 0.46 to 1.60, $I^2 = 0\%$, $\chi^2 = 0.94$, $df = 1$, $p = 0.33$).

3.5.6 *Total Duration of Training Per Week*

The overall dose-response relationships related to the volume specific modality of ‘total duration of training per week’ are illustrated in Figure 11. In this analysis a total duration of 31-60 minutes per week showed the largest effect on overall balance performance with a SMD_{wm} of 1.33 (3 studies; 4 intervention groups; 95% CI 0.77 to 1.89, $I^2 = 53\%$, $\chi^2 = 6.39$, $df = 3$, $p = 0.09$) and was calculated from 12 studies with 14 intervention groups.

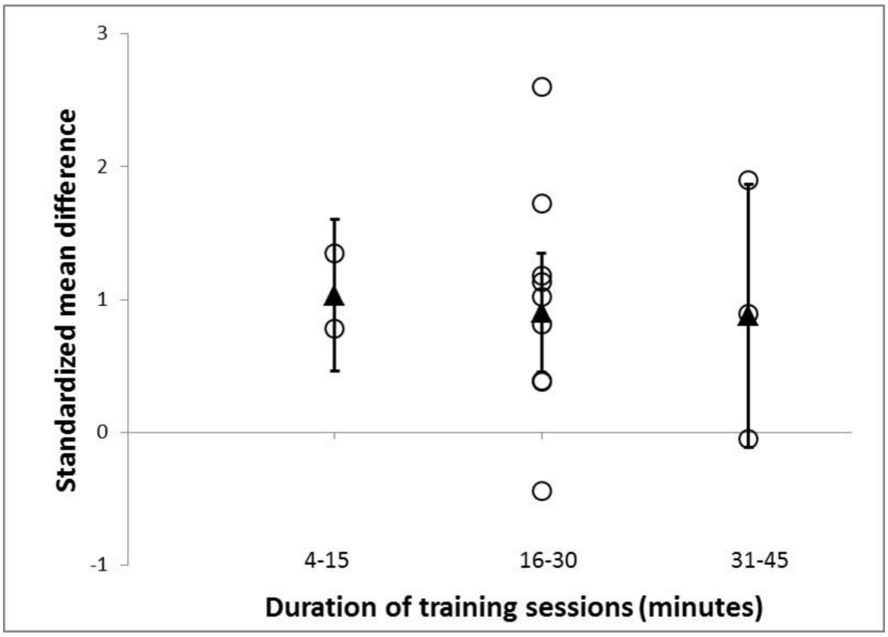


Fig. 12 Dose-response relationships of the training modality ‘duration of a single training session’ on measures of overall balance in adolescents. Between-subject standardized mean difference (SMD) for each study is depicted by a white filled circle, whereas black triangles represent weighted mean SMD of all studies in a category

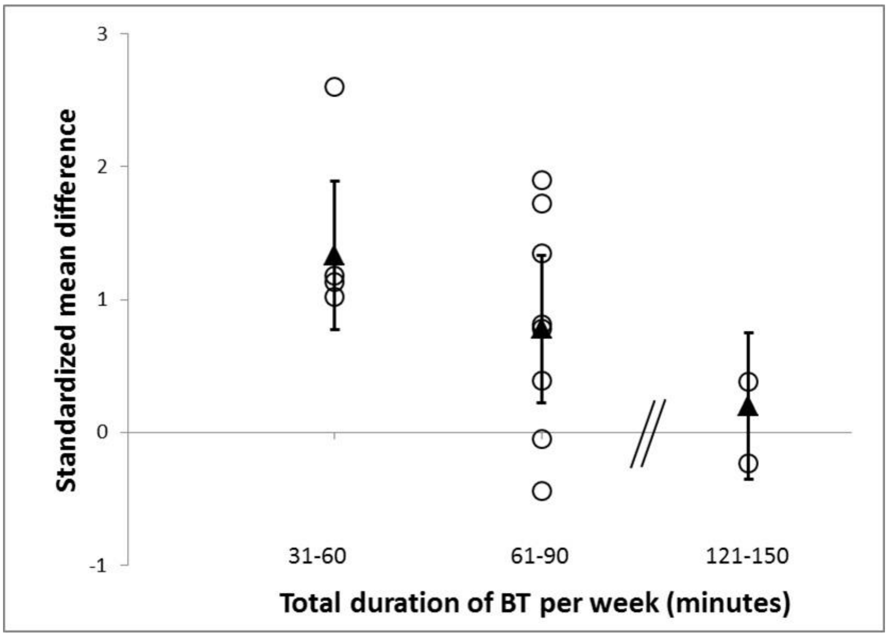


Fig. 13 Dose-response relationships of the training modality ‘total duration of training per week’ on measures of overall balance performance in adolescents. Between-subject standardized mean difference (SMD) for each study is depicted by a white filled circle, whereas black triangles represent weighted mean SMD of all studies in a category; *BT* balance training

4 Discussion

To the authors’ knowledge, this is the first systematic review and meta-analysis that examined and quantified overall effects of BT on measures of balance performance in youth and characterized dose-response relationships for BT modalities (i.e., training period, frequency, volume) to improve balance performance in adolescents. All in all, data from 17 controlled trials (20 intervention groups) were included in this review article. The main findings of these quantitative analyses were that (1) BT has moderate effects on static balance and large effects on dynamic balance, (2) BT is a highly effective method to improve balance performance in youth irrespective of age, sex, training status, setting, and testing methods, (3) the examined training modalities (e.g. training period, training frequency) did not have a moderating effect on balance performance in healthy adolescents.

4.1 General Effectiveness of Balance Training

A number of review articles and meta-analyses have already examined either performance enhancing effects and/or dose-response relationships of BT in healthy young and old adults [14, 15] or the preventive effects of BT on sport-related lower limb injuries (e.g., ankle sprains, anterior cruciate ligament tears) in youth and young adults [61, 23, 30, 28, 25]. However, to date there has been no review or meta-analysis available that quantified the effects of BT on proxies of balance performance (i.e., static and dynamic balance) in youth. This analysis revealed that BT is highly effective as a means of enhancing measures of static and dynamic balance performance in healthy youth. Effects were moderate on proxies of static balance and large on measures of dynamic balance. These findings are comparable to the training induced effects found by Lesinski et al. [14] in healthy young adults (static/dynamic steady-state balance: $SMD_{wm} = 0.73$; proactive balance: $SMD_{wm} = 0.92$). In comparison to the results of Lesinksi et al. [15] for old adults (static steady-state balance: $SMD_{wm} = 0.51$; dynamic steady-state balance: $SMD_{wm} = 0.44$) the impact of BT on balance performance in youth is considerably higher. Adaptive mechanisms at the spinal [62] and supraspinal level [63] in terms of better inter- and intra-muscular coordination and changes in reflex transduction [63] are assumed to be responsible for BT induced performance increases. In old adults these adaptive mechanisms might be altered due to age-related, multi-causal neuromuscular changes, which might explain differences in effect sizes of BT on measures of balance performance compared to youth.

According to the concept of training specificity [64], content of training should imitate the demands of the respective sport-related activity. A recent meta-analysis by Kümmel et al. [17] examining the specificity of BT in healthy individuals provides evidence that this concept is also valid for BT. They concluded that BT results in task-specific performance improvements of the trained balance tasks and that these improvements are rarely or not transferable to non-trained balance tasks. This conclusion is supported by recent research by Freyler et al. [65]

showing that sensorimotor training and reactive balance training were followed by stimuli specific adaptions and balance performance was augmented when training and test paradigm coincided. Considering these findings, a specific, well-designed balance training comprising exercises mimicking the specific demands of a sport-related activity could improve both balance and sport-related performance. The work by Yaggie et al. [12], Taube et al. [66], Boccolini et al. [58], and Granacher et al. [18] has already documented the beneficial effects of BT on performance of sport-related activities (e.g., shuttle run, counter movement jump). Further, Mahmoud [13] provided evidence that a specific BT protocol for youth basketball players increases basketball-specific performance (e.g., dribbling and passing on wall targets, shooting around the free throw zone). In addition, the recently published work by Wälchli et al. [56] indicates that BT has to be age-specific in its content and demands as well to optimize the effects on balance performance. They showed that a child-oriented BT program, tailored to the needs of children, has a greater effect on static and dynamic balance performance in young-aged (6-7 years) than middle (11-12 years) and older-aged youth (14-15 years). Moreover, the child-oriented BT program increased physical performance (i.e., rate of torque development) in all age groups but revealed no age difference. Therefore, it seems helpful to integrate age-matched BT protocols into regular training regimes of youth (athletes) in order to maximize the muscular potential and thus improve sport-related performance concomitant to balance performance.

4.2 Impact of Moderator Variables on Balance Training Induced Effects

Contrary to our assumption, the subgroup analysis revealed no statistically significant differences for any of the tested moderator variables. However, we were able to identify potential sources for the observed magnitude in heterogeneity. Subgroup analysis revealed a considerable heterogeneity for the subgroups of children, untrained individuals, schools, and physical fitness tests, which might account for a large amount of the overall heterogeneity observed in this meta-analysis. In terms of chronological age, the considerable heterogeneity in children might reflect a higher variability in balance performance compared to adolescents and is supported by the wide CI of the corresponding SMD_{wm} for children (Table 4). Since the number of studies that examined the effects of BT in children is small, a further interpretation is rather speculative. However, a higher variability in balance performance might be caused by the immaturity of the balance control system in children compared to adolescents [21]. Alternatively, it could also be due to a lower level of balance performance at baseline. Further, we detected no statistically significant sex-specific effect for overall balance. Subgroup analysis for training status revealed a considerable heterogeneity for untrained individuals, although BT-induced effects on overall balance were large in both trained and untrained subjects (Table 4). The results might suggest that the responses of the neuromuscular and postural system to the applied BT protocols in untrained subjects are more variable because both systems are not used to BT-induced stimuli. Nevertheless, the findings of this sub-analysis indicate a high effectiveness of BT on balance performance in youth irrespective of the training status. Therefore, BT should be performed in addition to other training forms (e.g., resistance training, plyometrics) in order to increase balance and sport-related performance as suggested by the previously reported associations between balance, muscle strength and power [67] as well as youth training studies that demonstrate improved performance when balance training is incorporated prior to plyometric training [68]. Further, sub-analysis of setting-specific effects revealed a considerable amount of heterogeneity for BT in the school setting which might be caused by heterogeneous cohorts in school classes. Moreover, the analysis calculating effects for testing methods assessing proxies of overall balance revealed a considerable heterogeneity within the sub-group “physical fitness tests”. This high amount of between-study variability might be explained by inaccuracy and error of measurement produced by the assessor conducting the tests compared to biomechanical assessment apparatus.

4.3 Effects and Dose-Response Relationships following Balance Training in Adolescents

As pointed out in the previous section, this meta-analysis documented the general effectiveness of BT on balance performance (i.e., static and dynamic balance) in youth. We further investigated the effects of BT on proxies of static and dynamic balance as well as on overall balance in adolescents. Results indicate moderate to large effects of BT for static, dynamic, and overall balance. Compared to the effectiveness of BT in youth, performance increases for static and dynamic balance in adolescents are similar. Higher balance performance variability in children together with a higher and consistent performance level in adolescents might be responsible for the attenuated heterogeneity in adolescents and might also apply to differences in BT-induced effects on overall balance. To identify key training modalities that are responsible for the observed increases in overall balance performance in adolescents, we performed a multivariate random effects meta-regression analysis. The nonsignificant results indicated that none of the examined training modalities predicted the effects of BT on balance performance in adolescence. Further, the applied statistical model revealed zero explained variance ($R^2 = 0.00$). These findings imply that an additional training modality may have a major effect on balance training outcomes that was not assessed in our analysis. Training intensity could be a promising candidate, even though it is difficult to assess. In addition to meta-regression, a subgroup analysis was conducted for the subgroups within each training modality. Further, we interpreted the magnitude of effect size of modality specific subgroups to elaborate independent dose-response relationships following BT in adolescents. The analysed studies showed large variations in their training modalities. Training periods ranged from 4-12 weeks (in one case even longer; over a complete soccer season but without further specification [20]), frequencies from 2-7 times/week, total number of training sessions from 10-84, duration of a training session from 4-50 minutes and total duration of training per week from 40-150 minutes. The characterization of dose-response relationships revealed that, when considered individually and not as complete training protocol, training periods of 12 weeks, a frequency of two sessions per week, a total number of 24-36 training sessions, durations of 4-15 minutes of a single training session, and total durations of 31-60 minutes of BT per week were the most effective single training modalities for improvements in overall balance. Overall, it is apparent that these independently calculated training modalities to maximize improvements in overall balance performance in adolescents are comparable to those that were previously reported for healthy young and old adults [14, 15]. However, the nature of the specific responses to BT in adolescents shows little differences to those of older age groups and is discussed for the single training modalities separately.

4.3.1 *Training Period*

This analysis revealed that BT lasting 12 weeks is most effective for improving overall balance in adolescents. As illustrated in Figure 7, shorter training periods produced lower SMD_{wm}, whereas longer training periods were effective as well. However, Malliou et al. [20] showed that even long lasting BT as part of regular training in elite adolescent soccer players over a whole season, estimated at approximately 40 weeks, is also highly effective. Regular soccer training accompanied by frequent BT improved dynamic balance performance and additionally decreased the occurrence of lower limb injuries by more than 25% compared to the control group. Therefore, in view of balance performance improvement and its concurrent injury preventive character, BT seems to be very helpful on a long-term basis. But due to the limited number of studies examining effects of BT in the long-term range (>12 weeks) it is not possible to prognosticate on the long-term effects of BT in youth. Overall, these findings are in line with the dose-response relationships for healthy young (16-40 years) and old (+65 years) adults quantified by Lesinski et al. [14, 15] (Table 7), which were in favour of a 11-12 weeks BT program.

Table 8 Dose-response relationship for balance training in healthy adolescents in comparison to healthy young and old adults

Training modalities[a]	Results/most effective dose			
	Healthy adolescents (mean age 12-19 yrs)	Healthy young adults (age 16-40 yrs) [14]	Healthy old adults (age +65 yrs) [15]	
	Overall balance (13 studies included)	Static/dynamic steady-state balance (16 studies included)	Overall balance (23 studies included)	Static steady-state balance (12 studies included)
Training period (weeks)	12	11-12	11-12	11-12
Trainings frequency (times per week)	2	3	3	3
Number of training sessions	24-36	16-19, 36-39[b]	36-40	36-40
Duration of a single training session (min)	4-15	11-15[c]	31-45	31-45
Total duration of BT per week (min)	31-60	N/A	91-120	121-150[d]
Number of exercises per training session	N/A	4	N/A	N/A
Number of sets/reps per exercise	N/A	N/A	N/A	N/A
Duration of a single balance exercise (s)	N/A	21-40	N/A	N/A

BT balance training, *N/A* not available, *reps* repetitions; *yrs* years

[a] Training modalities were calculated independently (i.e., modality specific) and have to be considered individually.

[b] Almost identical effect sizes (1.12 vs. 1.09)

[c] Most included studies performed BT without warm up and/or cool down and thus were shorter in duration compared to youth and old adults.

[d] Only one study

4.3.2 *Training Frequency*

The findings of this analysis, documented in Figure 8, indicated that two BT sessions per week provide higher performance improvements for overall balance than training frequencies of three, five or even seven times per week. Compared to recent dose-response analyses in healthy young and old adults [14, 15] that reported three BT sessions per week as most effective, the results of the present analysis are in favour of two BT sessions per week. These findings might be explained by longer periods required for neuromuscular recovery and adaptation processes in adolescents compared to adults. When continuous BT stimuli are applied too early, ongoing processes of recovery and adaptation might be interrupted and the BT-induced effects cannot develop their full impact on balance performance. On the other hand, longer periods of recovery between training sessions protect youth from injuries induced by fatigue or overuse. However, the results are preliminary and should be interpreted carefully.

4.3.3 *Training Volume (Number of Training Sessions)*

In terms of the number of training sessions, this analysis revealed that 24-36 training sessions in total had the largest effects on proxies of overall balance. As illustrated in Figure 9, an inverse U-shaped relation might exist, indicating that a higher (>42 sessions) and lower number

(10-18 sessions) of overall training sessions tend to be less effective. The occurrence of this type of relation has been well documented in the fields of biology, toxicology and public health [69] and seems to be a reasonable phenomenon for BT in adolescents as it was already reported for adults [14, 15]. However, this interpretation of the results is speculative, since the overall number of studies is rather small and the actual existence as well as the type of the relation was not statistically verified. Nevertheless, these results are partly in accordance with findings of Lesinski and colleagues for healthy young [14] and old [15] adults, which indicated largest effects in both age groups for an overall number of 36-40 training sessions. But compared to the older age groups, fewer training sessions in total seem to be more effective in improving overall balance. This might be also interpreted as a result of longer neuromuscular recovery and adaptation processes to BT-induced stimuli in youth.

4.3.4 Training Volume (Duration of a Single Training Session and Total Duration of Training Per Week)

We found that a duration of 4-15 minutes for a single training session is most effective for improving overall balance performance in adolescents. As Figure 10 illustrates, single training sessions of 16-30 minutes are highly effective as well but with a closer confidence interval and a larger number of studies than shorter durations. On basis of these results, one might argue that durations of 16-30 minutes are more expectable to be most effective in increasing balance performance. Dose-response relationships for the total duration of training per week revealed that durations of 31-60 minutes had the largest enhancing impact on overall balance. Data shown in Figure 11 indicate that the longer the training duration in total per week the lesser the effect of BT on overall balance. In light of overuse and fatigue, it seems evident that overly extensive durations of a single training session and of training sessions in total diminish the performance improvements induced by BT. However, the results of this analysis for duration of a single session for overall balance are not congruent with those for steady-state balance in healthy young adults (11-15 min) and overall balance (31-45 min) as well as static steady-state balance (31-45 min/week) in healthy old adults as seen in Table 7. Further, results for total duration of BT per week differed from those of healthy old adults for overall balance (91-120 min/week) and static steady state balance (121-150 min/week) as well, whereas dose-response relationships for total duration of BT per week in healthy young adults were not examined.

4.4 Limitations

The considerable heterogeneity (i.e., I^2 = 66-83%) among all studies is the strongest limitation of this systematic review and meta-analysis. Subgroup analysis helped to identify potential reasons for the observed magnitude in heterogeneity. However, future studies should focus on standardised balance outcomes as well as on the use of biomechanical test methods instead of physical fitness tests to assess the different components of balance performance (i.e., static/dynamic steady-state, reactive, and proactive balance). Another limitation is that we aggregated balance outcomes from different balance components (proactive and quasi dynamic conditions) and classified these as dynamic balance because of a limited number of available studies. Thus, conclusions on single balance components (e.g., proactive/reactive balance) are not legitimate. A general problem in specifying dose-response relationships was the lack of reporting the intensity of BT exercises in all studies which is why we were not able to compute those for the training modality “exercise intensity”. Further, we were not able to control for interdependencies in the training protocol since dose-response relationships were calculated independently. Therefore, comparative studies are needed in addition to meta-analyses to examine the effects of one training modality while the other modalities are kept constant. Future studies should also assess the effects of specific BT programs on single balance components (static/dynamic steady-state, proactive, and reactive) to help designing BT programs that train selected balance components. In addition, only two out of 17 studies had a PEDro score above six and thus a reduced risk of bias by blinded assignment and blinding for outcome assessment. Thus, high methodological quality studies are needed to further our knowledge of BT in youth and estimate the effects of BT on balance performance. Moreover, high quality research would help to characterize interrelated component-specific dose-response relationships and component-specific performance enhancing effects.

5 Conclusions

This systematic review and meta-analysis demonstrated that BT is a highly effective means for improving static and dynamic balance in youth irrespective of age, sex, training status, setting, and testing method. Our dose–response analyses revealed that the examined training modalities (e.g. training period, training frequency) did not have a moderating effect on balance performance in healthy adolescents. Thus, it appears that an additional but so far unidentified training modality (e.g. training intensity) could be a likely agent. Future studies are needed to elucidate relevant BT-modalities that allow the analysis of dose–response relationships following BT in youth.

Compliance with Ethical Standards

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Conflict of Interest

Arnd Gebel, Melanie Lesinski, David G. Behm and Urs Granacher declare that they have no conflicts of interest relevant to the content of this review.

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Publication II

EFFECTS OF INCREASING BALANCE TASK DIFFICULTY ON POSTURAL SWAY AND MUSCLE ACTIVITY IN HEALTHY ADOLESCENTS

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Effects of increasing balance task difficulty on postural sway and muscle activity in healthy adolescents

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Abstract

Evidence-based prescriptions for balance training in youth have recently been established. However, there is currently no standardized means available to assess and quantify balance task difficulty (BTD). Therefore, the objectives of this study were to examine the effects of graded BTD on postural sway, lower limb muscle activity and coactivation in adolescents. Thirteen healthy high-school students aged 16 to 17 volunteered to participate in this cross-sectional study. Testing involved participants to stand on a commercially available balance board with an adjustable pivot that allowed six levels of increasing task difficulty. Postural sway (i.e., total center of pressure [CoP] displacements) and lower limb muscle activity were recorded simultaneously during each trial. Surface electromyography (EMG) was applied in muscles encompassing the ankle (m. tibialis anterior, medial gastrocnemius, peroneus longus) and knee joint (m. vastus medialis, biceps femoris). The coactivation index (CAI) was calculated for ankle and thigh muscles. Repeated measures analyses of variance revealed a significant main effect of BTD with increasing task difficulty for postural sway ($p<0.001$; $d=6.36$), muscle activity ($p<0.001$; $2.19<d<4.88$), and CAI ($p<0.001$; $1.32<d<1.41$). Multiple regression analyses showed that m. tibialis anterior activity best explained overall CoP displacements with 32.5% explained variance ($p<0.001$). The observed increases in postural sway, lower limb muscle activity, and coactivation indicate increasing postural demands while standing on the balance board. Thus, the examined board can be implemented in balance training to progressively increase BTD in healthy adolescents.

Keywords: balance training, training intensity, youth, muscle coactivation, balance strategy

INTRODUCTION

The development of balance with its specific components (i.e., static/dynamic steady-state, reactive, proactive balance) (Shumway-Cook and Woollacott, 2012) represents an important prerequisite for motor skill acquisition in youth (Roncesvalles et al., 2001; Mickle et al., 2011). There is evidence that balance training produces moderate-to-large effects on motor skills, balance, and sport-specific performance in youth (Malliou et al., 2004; Yaggie and Campbell, 2006; Granacher et al., 2010; Mahmoud, 2011; Boccolini et al., 2013; Walchli et al., 2017) and has the potential to reduce the risk of lower limb injuries in healthy adolescents (Malliou et al., 2004; Emery et al., 2005) and young adults (Verhagen et al., 2004). In order to optimize the effectiveness of balance training, it is crucial to elucidate the optimal combination and dosage of training modalities (e.g., training period, frequency, and volume). While training period, frequency, and volume can easily be assessed for balance training, it is more difficult to quantify balance intensity and/or balance task difficulty (BTD). This could be due to the fact that postural control is primarily neuronally and not energetically driven. In their narrative review, Taube et al. (2008) reported that adaptive mechanisms related to balance training mostly occur on a spinal (e.g., increased presynaptic inhibition) and supraspinal level (e.g., decreased corticospinal excitability). Energetically driven physical qualities like muscle strength can easily be monitored using the one repetition maximum and/or rating of perceived exertion scales (e.g., BORG, OMNI) (Robertson et al., 2003; Robertson et al., 2004). Previously, attempts have been made to assess balance training intensity. However, either another training modality (e.g., frequency, duration) was misinterpret as balance training intensity or psychometric instruments (e.g., scales) only valid for other kinds of training (e.g., endurance) were used to measure intensity (Farlie et al., 2013). For instance, the BORG rating scale of aerobic exertion (Means et al., 2005) was used to quantify balance exercise intensity. Additionally, ratings of perceived exertion do not seem to be an adequate measure to quantify dosage of balance training as they measure exertion and not intensity per se. In fact, they were only validated for strength and endurance training but not for balance training (Robertson et al., 2003; Robertson et al., 2004; Farlie et al., 2013).

Consequently, it is not surprising that recently published systematic reviews and meta-analyses on the effects and dose-response relationships of balance training on balance performance in youth (Gebel et al., 2018), young (Lesinski et al., 2015a) and old adults (Lesinski et al., 2015b; Farlie et al., 2018) were not able to identify a single training modality to predict balance training related effects (Farlie et al., 2018; Gebel et al., 2018). This could be due to the fact that only a limited number of training modalities (i.e., frequency, period, and volume) was included in these analyses. Consequently, Gebel et al. (2018) postulated that a measure of training intensity and/or BTD might be a promising candidate to predict balance outcomes.

The research work of Farlie et al. (2018) clearly indicated the problem, in terms of the absence of psychometrically valid tools, to quantifying balance training intensity. Therefore, it appears plausible to argue that with balance training, intensity should be replaced by a different training modality. A promising candidate could be BTD, which can be easily modified by manipulating the base of support (BoS) and sensory inputs (proprioceptive and visual). In this context, Mühlbauer et al. (2012) showed that BTD can be increased by continuously reducing the BoS. Further, studies investigated the effects of increasing BTD on neuromuscular activity. Results showed that lower limb muscle activity (Dohm-Acker et al., 2008; Cimadoro et al., 2013) and coactivation (Donath et al., 2016) increased with increasing BTD. In fact, recent studies on the progression of BTD were mainly conducted using various environmental conditions to manipulate posture (e.g., BoS, training device, surface, vision, etc.) (Dohm-Acker et al., 2008; Muehlbauer et al., 2012; Cimadoro et al., 2013; Donath et al., 2016). However, a growing number of studies (Giboin et al., 2015; Freyler et al., 2016; Kümmel et al., 2016; Giboin et al., 2018; Kiss et al., 2018; Makhlouf et al., 2018; Nagy et al., 2018) has clearly shown that balance is a highly task-specific. Therefore, it has to be trained and tested according to the specifics of the underlying task. Consequently, it is not possible to find answers to the question of increasing balance task difficulty using different balance tools (e.g., balance pad, board etc.). This research question can only be answered if a single balance tool is applied that allows a gradual increase of balance task difficulty. Scientific evidence is scarce on how a graded increase of BTD using BoS only affects postural sway, lower limb muscle activity and coactivation. Based on the work of Shumway-Cook and Woollacott (1985) as well as Steindl et al. (2006), we expected that the effects of BTD on postural sway and muscle activation in adolescents were not comparable to those in adults as the processes of growth and maturation are not linear. However, to the authors' knowledge, there are currently no studies available that examined the specific effects of a graded BTD on postural sway and neuromuscular activity in adolescents.

Therefore, the objectives of this study were to examine the effects of a gradually increasing BTD (i.e., balance board with adjustable BoS) on postural sway, lower limb muscle activity and coactivation in healthy adolescents. Based on the relevant literature, we hypothesized increases in postural sway (Muehlbauer et al., 2012; Cimadoro et al., 2013), lower limb muscle activity (Soderberg et al., 1991; Dohm-Acker et al., 2008; Cimadoro et al., 2013) and coactivation (Donath et al., 2016) with a gradually increased BTD. Moreover, we expected that the ankle muscles are mainly responsible (Dohm-Acker et al., 2008) for increases in postural sway with increasing BTD.

MATERIALS AND METHODS

Participants

Thirteen (3 female / 10 male) healthy high school students aged 16-17 years volunteered to participate in this study. Age at peak height velocity (PHV) was calculated using the sex-specific equation of Mirwald et al. (Mirwald et al., 2002). The participants' maturity level ranged from 2.3 to 4.5 years post PHV. Participants' characteristics are summarized in Table 1. The study was approved by the local ethics committee of the University of Potsdam (application no. 18/2017). All participants and their legal guardians gave their written informed consent prior to the onset of the study. The experiment was conducted according to the latest version of the declaration of Helsinki. An a priori power analyses using G*Power (Version 3.1.9.2, University of Kiel, Germany) (Faul et al., 2009) one group and a repeated measure ANOVA design with 6 measurements yielded a total sample size of N = 10 (effect size $f = 0.4$, $\alpha = 0.05$), with an actual power of 0.91 (critical F-value = 2.42). Effect size was estimated using previously published work on the effects of different unstable supports on muscle activity in young adults (Cimadoro et al., 2013).

Experimental procedure

A single group design was used to examine the effects of increasing BTD on balance performance and leg muscle activity/coactivation in adolescents. For this purpose, participants attended the lab for one experimental session. Every session started with a standardized familiarization phase to introduce the balance task and the multi-directional balance training device (balance board). Subsequently, surface electrodes were attached to the shank and thigh muscles of the non-dominant leg. Leg dominance was assessed using the lateral preference inventory (Coren, 1993). Thereafter, participants performed three sets of six balance tasks. Each set consisted of a different randomized order of the six levels of BTD. Overall, testing of one participant comprised 18 trials with each trial lasting 30 s. To assess postural sway, centre of pressure (CoP) displacements were measured using two measuring sensor mats (novel GmbH, München, Germany) which were placed on the balance board (Wobblesmart©, Artzt GmbH, Dornburg, Germany). Lower limb muscle activity was assessed using surface electromyography (EMG) and synchronized with CoP data. Anthropometrics were tested using a stadiometer (seca 213, seca Gmbh, Hamburg, Germany) and a bioimpedance analysis system (InBody 720, BioSpace, Seoul, Korea).

Table 1: Participants' characteristics (mean ± standard deviation)

	Total (*N* = 13)	male (*n* = 10)	female (*n* = 3)
Age [years]	16.9 ± 0.5	17.1 ± 0.6	17.1 ± 0.4
Body height [cm]	176.4 ± 6.5	178.1 ± 5.5	170.9 ± 4.9
Body mass [kg]	67.4 ± 6.2	68.1 ± 6.0	70.2 ± 4.6
Maturity status [years after PHV]	3.0 ± 0.6	2.9 ± 0.4	3.7 ± 0.6

Note: PHV = peak height velocity

Balance task

All balance tasks were executed without shoes in bipedal upright stance on the balance board for a duration of 30 s. Every test trial started from a standardized position where participants held on to a handrail in front of them to allow quiet stance and to bring the balance board in horizontal position. During testing, participants were asked to stand in bipedal stance with knees slightly flexed at approximately 30°, to hold hands akimbo and to fixate their gaze at a cross on a nearby wall (3 m distance). During measurement, participants were instructed to keep the balance board as still as possible in horizontal plane and to avoid ground contact with the board edges. BTD was implemented into our experimental paradigm using a commercially available multi-directional balance board (Wobblesmart©, Artzt GmbH, Dornburg, Germany). The board (standing platform with a diameter of 39 cm) is equipped with a mechanically adjustable pivot to increase task difficulty. The mechanism integrated in the pivot continuously elevates the balance platform by a gradual clockwise rotation from initially 6.5 cm (level 1) to 8 cm (level 6) which simultaneously reduces the BoS diameter of the pivot from approximately 14 to 4 cm (Figure 1A).

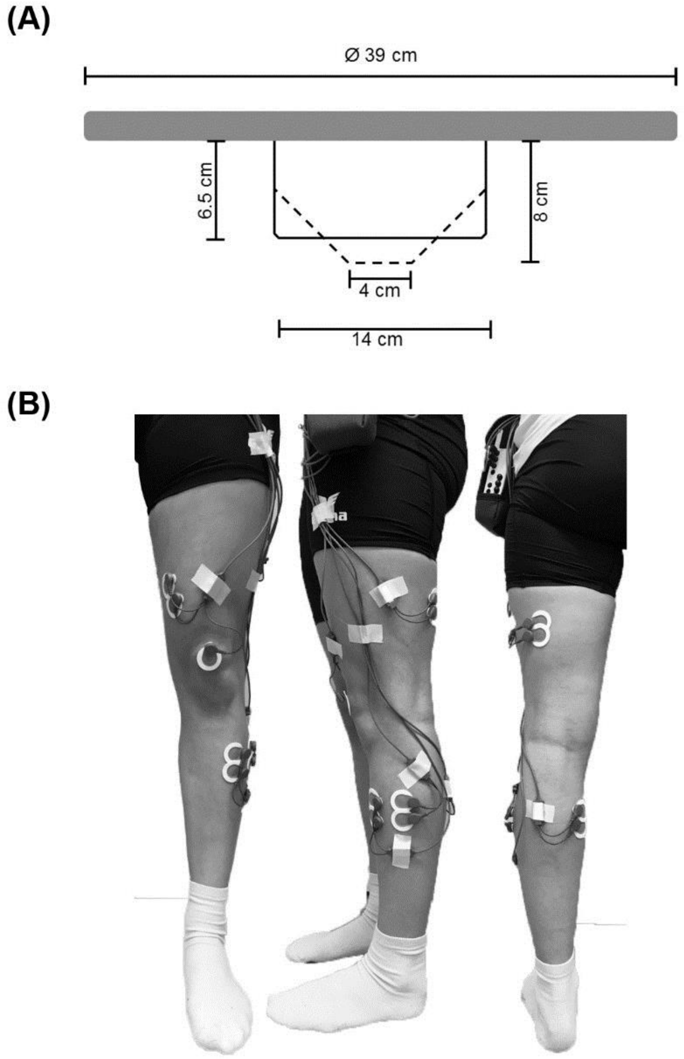

Figure 1 (A) Schematic representation of the used balance board and its mechanically adjustable pivot. By rotating clockwise, the pivots diameter of the contact area is reduced (reduction in BoS) and the level of BTD increases. Solid lines represent the pivots position at BTD level 1, dashed lines represent the pivots position at BTD level 6. (B) Electrode sights used for respective EMG recordings of the musculus tibialis anterior (TA), m. peroneus longus (PL), m. gastrocnemius medialis (GM), m. vastus medialis (VM) and m. biceps femoris (BF) from ventral, lateral, and dorsal view.

Measurement of postural sway

Postural sway in the form of total CoP displacements (combined medio-lateral and anterior-posterior direction) was assessed as a measure of performance on the balance board for 30 s (Scoppa et al., 2013) using a pressure distribution measuring system (Pedar©, novel GmbH, München, Germany). For this purpose, two sensor mats (Posturo S2094, novel GmbH, München, Germany) were placed on the balance board and fixed with double sided adhesive tape to prevent mats from slipping. The CoP displacements were recorded with 220 sensors (sensor dimensions: 20x20 mm) per mat (mat dimensions: 440x220 mm) at the maximum sampling rate (40 Hz) allowed by the system using the Posturo 32 Expert software (version 25.3.6, novel GmbH, München, Germany). Synchronization between CoP and EMG data was achieved using a direct link between the Pedar©

and EMG system. The Pedar© system (Posturo Sync Box, novel GmbH, München, Germany) generated a TTL synchronization signal from onset to offset of every trial which was received and recorded by the EMG system (TeleMyo 2400R Analog Output Receiver, Noraxon©, Scottsdale, AZ, USA). Mean total CoP displacements were calculated for every participant and each level of BTD.

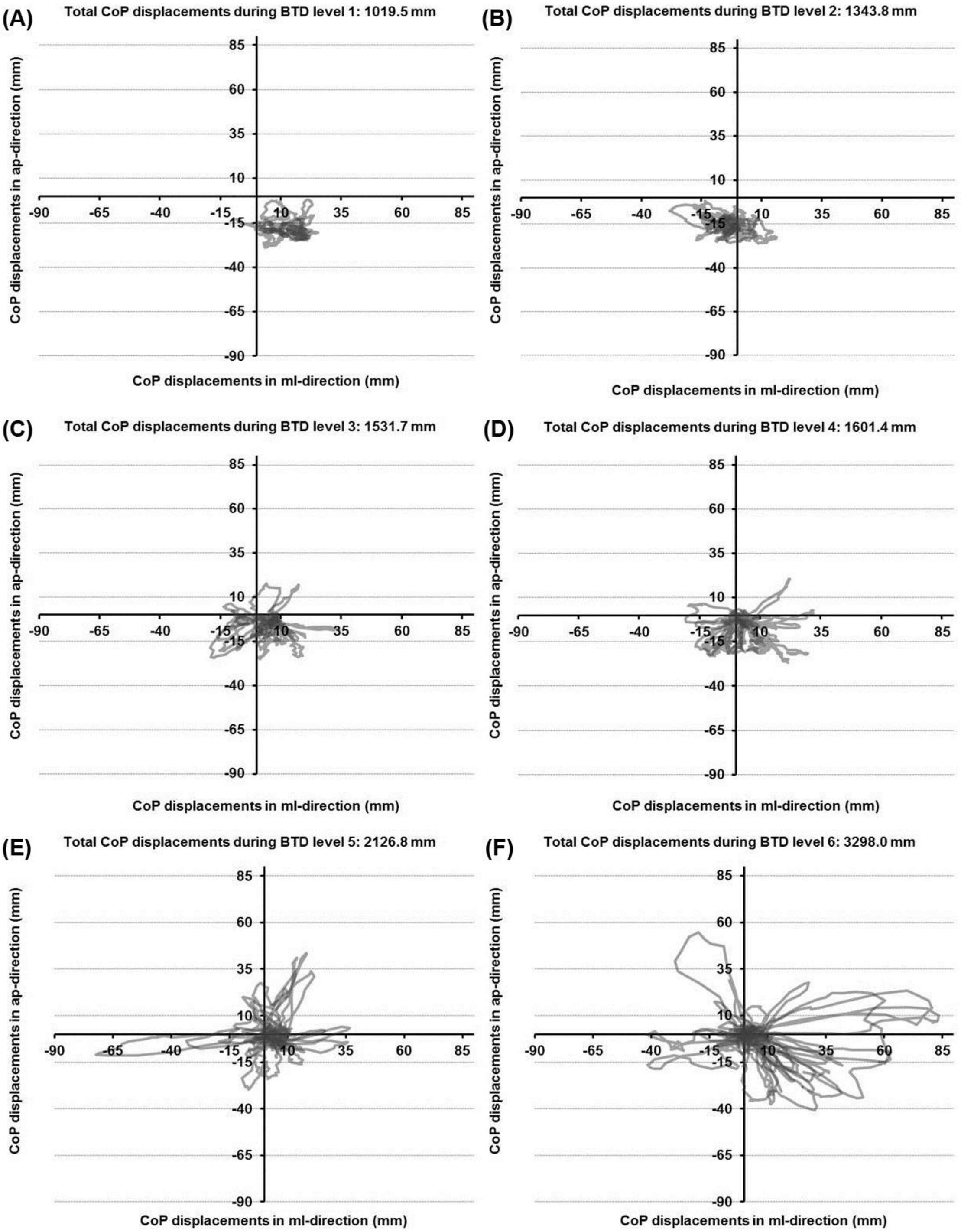

Figure 2 Center of pressure (CoP) displacements in anterior-posterior (ap) and medio-lateral (ml) directions for a representative participant during all six levels of balance task difficulty (BTD) for level 1 to level 6 (A to F).

Measurement of muscle activity

During each test trial, EMG activity of ankle (m. tibialis anterior [TA], medial gastrocnemius [GM], peroneus longus [PL]) and thigh muscles (m. vastus medialis [VM], biceps femoris [BF]) was recorded using circular bipolar surface electrodes (Ambu©, type Blue Sensor P-00-S/50, Ag/AgCl,13.2 mm, center-to-center distance 25 mm, Ballerup, Denmark). According to SENIAM guidelines (Hermens et al., 2000) and prior to the location of the electrodes on the respective muscle bellies (Figure 1B), the skin was prepared by shaving, slightly roughening, degreasing, and disinfecting to obtain an inter-electrode impedance below 5 kΩ. EMG signals were amplified, transmitted telemetrically (TeleMyo 2400 G2, Noraxon©, Scottsdale, AZ, USA), and recorded at a sampling rate of 1,500 Hz. For offline analysis, raw data were digitally bandpass filtered (10 - 500 Hz) followed by a moving-root-mean-square filter with a time constant of 50 ms according to the processing routine previously reported (Prieske et al., 2014; Prieske et al., 2017) running the MyoResearch XP Master edition software (version 1.08.17, Noraxon©, Scottsdale, AZ, USA). As this cross-sectional study was carried out using a within-subject design in a single session with a fixed electrode setup, non- normalized EMG data was used for analyses (De Luca, 1997; Halaki and Gi, 2012). EMG was defined as the mean amplitude voltage in the time interval determined by the TTL-signal. First, the mean EMG amplitude was averaged across the 3 trials within every of the 6 conditions for each muscle and participant and used for analyses. Further, to analyse the effect of BTD on ankle and thigh muscle activity, the aggregated mean EMG amplitude was calculated for all ankle (TA, GM, and PL) and thigh (VM and BF) muscles. We applied this more global approach of analysis additionally because the multi-directionality of the balance task does not allow for differentiation between agonistic and antagonistic muscles. Moreover, muscle coactivation was computed for GM and TA as well as for VM and BF from the respective EMG mean amplitudes. We used the following formula according to Donath et al. (Donath et al., 2016) to calculate the coactivation index (CAI):

$$CAI = \frac{Mean\ EMG\ amplitude\ of\ the\ less\ active\ muscle}{Mean\ EMG\ amplitude\ of\ the\ more\ active\ muscle}$$

The CAI (arbitrary values between 0 and 1) is used as an estimator of increasing joint stiffness (Donath et al., 2016) to maintain stability by a more rigid posture (Hortobágyi and DeVita, 2000; Benjuya et al., 2004).

Statistical analyses

All statistical tests were performed using SPSS (Version 25, IBM, Chicago, IL, USA). Behavioural (total CoP-displacements) and electrophysiological (EMG) data were tested for normal distribution using the Shapiro-Wilk test. Repeated measures analyses of variance (rmANOVA) were computed separately for postural sway (total CoP displacements), lower limb muscle activity (for individual muscles and aggregated ankle and thigh muscles), and CAI (for TA-GM and VM-BF) as dependent variables. The six levels of BTD were added as repeating factors. If significant main effects of BTD were registered, post hoc tests were applied using Bonferroni-corrected paired t-tests. Thus, it was possible to identify BTD-specific increases in postural sway (total CoP displacements), muscle activity (mean EMG amplitude for ankle and thigh muscles respective), and muscle coactivation (CAI for GM-TA and VM-BF) between single BTD levels. Where appropriate, the Greenhouse-Geisser correction for non-sphericity was applied. In addition, two forward multiple regression analyses were applied to identify which set of muscles (ankle and/or thigh muscles) and single muscles (TA, PL, GM, VM, and BF) best predict total CoP displacements. The level of significance for all statistical analyses was set at $p \leq 0.05$. Effect estimates of partial eta-squared (η_p^2) were converted into

Cohen's *d* and interpreted according to Cohen (1988) with ≤ 0.2 as small, ≤ 0.5 as medium, and ≤ 0.8 as large effect.

RESULTS

Effects of balance task difficulty on postural sway

The CoP displacements in anterior-posterior and medio-lateral direction for a representative participant across the six levels of BTD are given in Figure 2 A-F. The rmANOVA revealed a large main effect of BTD ($F_{(2.4,\ 29.4)} = 121.6$, $p < 0.001$; $d = 6.36$) for postural sway (total CoP displacements). Post hoc tests identified significant differences in postural sway (Figure 3) between all levels (all *p*-values ≤ 0.005, $1.52 \leq d \leq 5.91$) except between level 1 and 2 as well as between level 3 and 4.

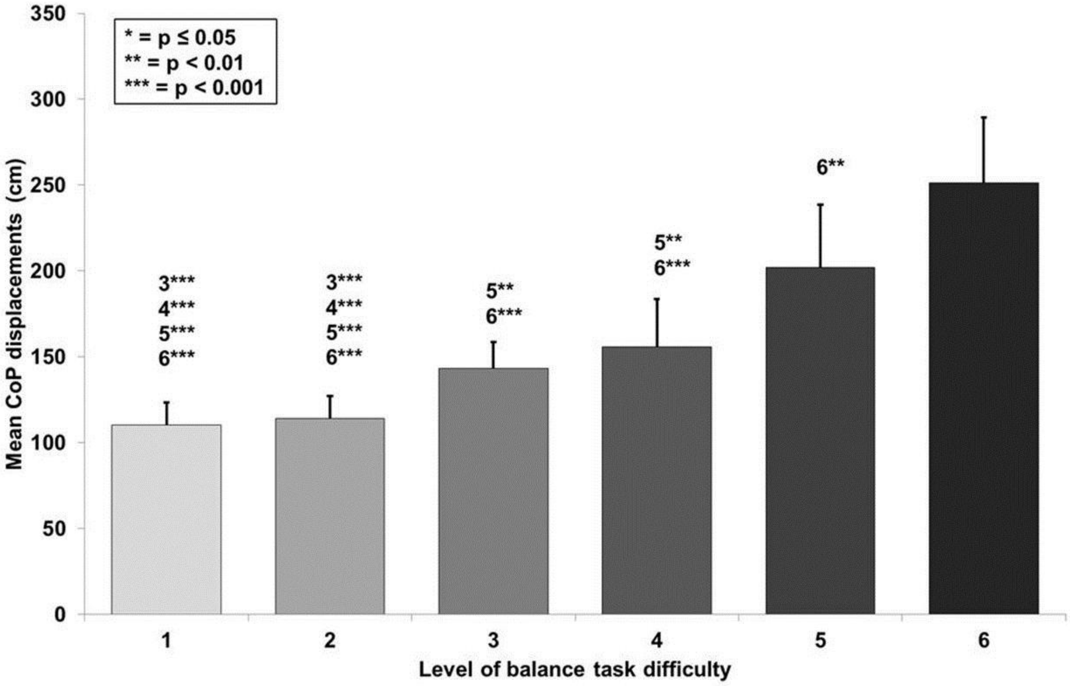

Figure 3 Values of the mean center of pressure (CoP) displacements with standard deviation for all six levels of balance task difficulty. Significant differences between levels are indicated by level number with respective asterisks according to the p-values defined in the legend.

Effects of balance task difficulty on lower limb muscle activity

Statistical analyses revealed significant large-sized effects ($p < 0.001$, $2.19 \leq d \leq 4.88$, Table 2) of increasing task difficulty on the individual muscles' activity (i.e., TA, GM, PL, VM, BF). Adjusted post-hoc tests showed significant differences in muscle activity between low and high levels of task difficulty (all *p*-values ≤ 0.043, Table 2).

Table 2 Mean EMG amplitudes for the individual muscles and the six levels of balance task difficulty.

	Level of balance task difficulty (Mean ±SD)						RmANOVA		Post-hoc	
	1	2	3	4	5	6	*p*-value	Cohen's *d*	Difference between levels	*p*-values
TA [µV]	10.4 ± 10.9	12.4 ± 12.9	31.2 ± 19.9	46.2 ± 29.8	66.5 ± 38.9	69.2 ± 26.5	<0.001	3.64	1 and ≥ 3; 2 and ≥ 3; 3 and ≥ 4; 4 and 5	≤ 0.022
GM [µV]	12.9 ± 5.2	20.6 ± 13.8	47.6 ± 30.1	49.4 ± 30.3	60.6 ± 31.1	62.1 ± 32.8	<0.001	2.63	1 and ≥ 3; 2 and ≥ 5; 3 and ≥ 5; 4 and 6	≤ 0.043
PL [µV]	13.1 ± 7.8	17.6 ± 7.4	31.7 ± 10.9	39.7 ± 12.7	47.9 ± 15.8	46.8 ± 11.2	<0.001	4.88	1 and ≥ 2; 2 and ≥ 3; 3 and ≥ 4; 4 and ≥5	≤ 0.027
VM [µV]	9.5 ± 8.5	9.1 ± 7.8	17.7 ± 10.2	22.1 ± 11.5	27.5 ± 11.6	28.1 ± 11.7	<0.001	3.10	1 and ≥ 3; 2 and ≥ 3; 3 and ≥ 5	≤ 0.025
BF [µV]	12.2 ± 11.4	14.8 ± 11.3	21.7 ± 13.5	21.9 ± 8.9	26.2 ± 7.0	28.3 ± 8.3	<0.001	2.19	1 and ≥ 4; 2 and ≥ 4	≤ 0.015

Note: BF = musculus biceps femoris; GM = m. gastrocnemius medialis; PL = m. peroneus longus; TA = m. tibialis anterior; VM = m. vastus medialis

A large main effect of BTD was observed for ankle muscle activity ($F_{(1.9,\ 72.5)} = 81.5$, $p < 0.001$, $d = 2.93$) in terms of mean EMG amplitude across the muscles (TA, GM, and PL). Post-hoc tests with Bonferroni correction showed significant differences in muscle activity (Figure 4A) dependent on BTD between all levels (all p-values ≤ 0.039, $0.34 \leq d \leq 2.53$) except between level 5 and 6.

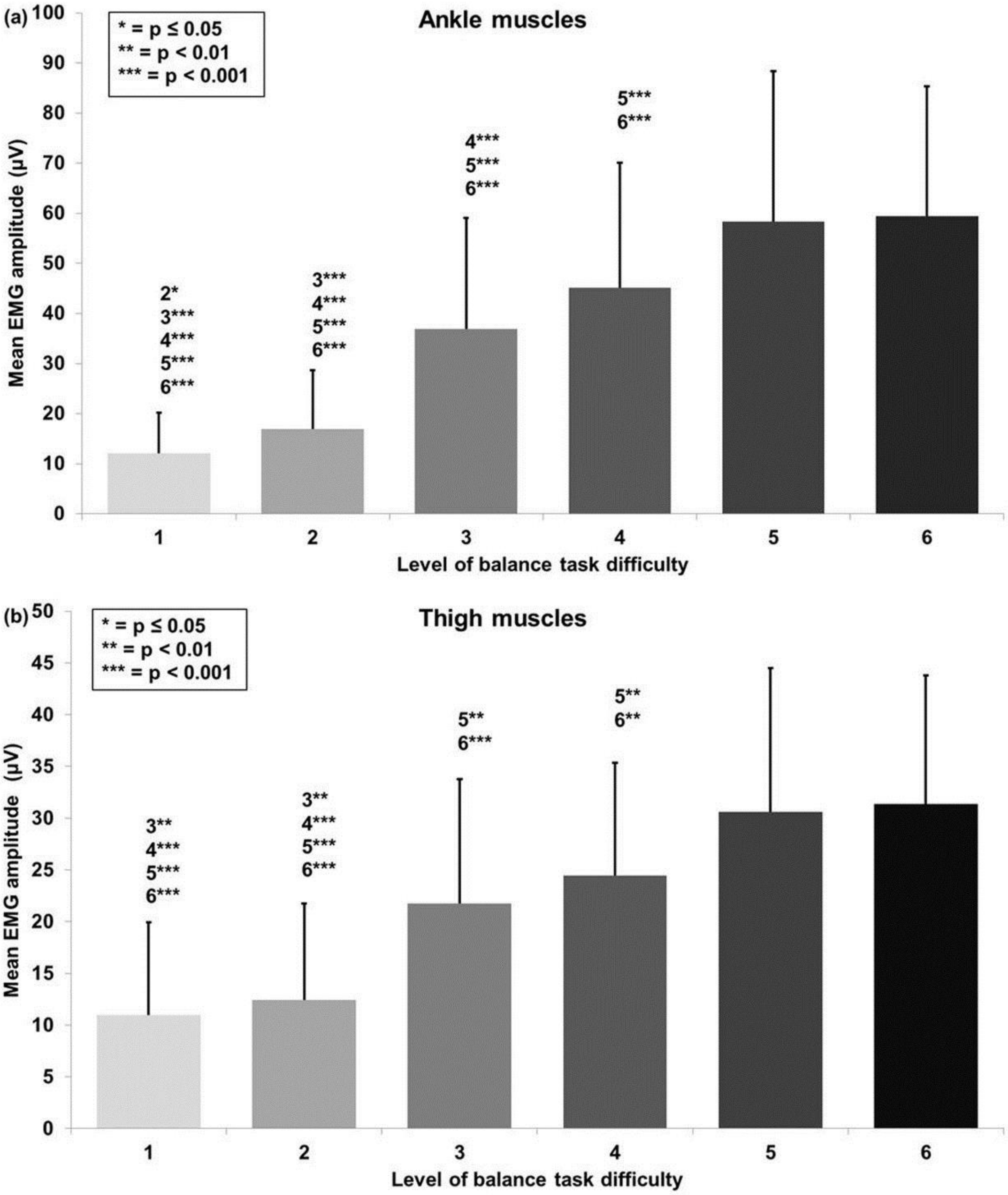

Figure 4 Absolut mean EMG amplitude values with standard deviation for (A) the ankle (tibialis anterior, peroneus longus, gastrocnemius medialis) and (B) thigh muscles (vastus medialis, biceps femoris) and all six levels of balance task difficulty. Significant differences between levels are indicated by level number with respective asterisks according to the p-values defined in the legend.

Thigh muscle activity (VM, BF) showed a large main effect for BTD ($F_{(2.5,\,63.3)} = 40.4$, $p < 0.001$, $d = 2.54$) as well. Pairwise comparison with corrected level of significance for multiple comparison showed significant differences in thigh muscle activity (Figure 4B) dependent on BTD between all levels (all p-values ≤ 0.008, $0.50 \leq d \leq 1.74$) except between level 1 and 2, between level 3 and 4 as well as between level 5 and 6.

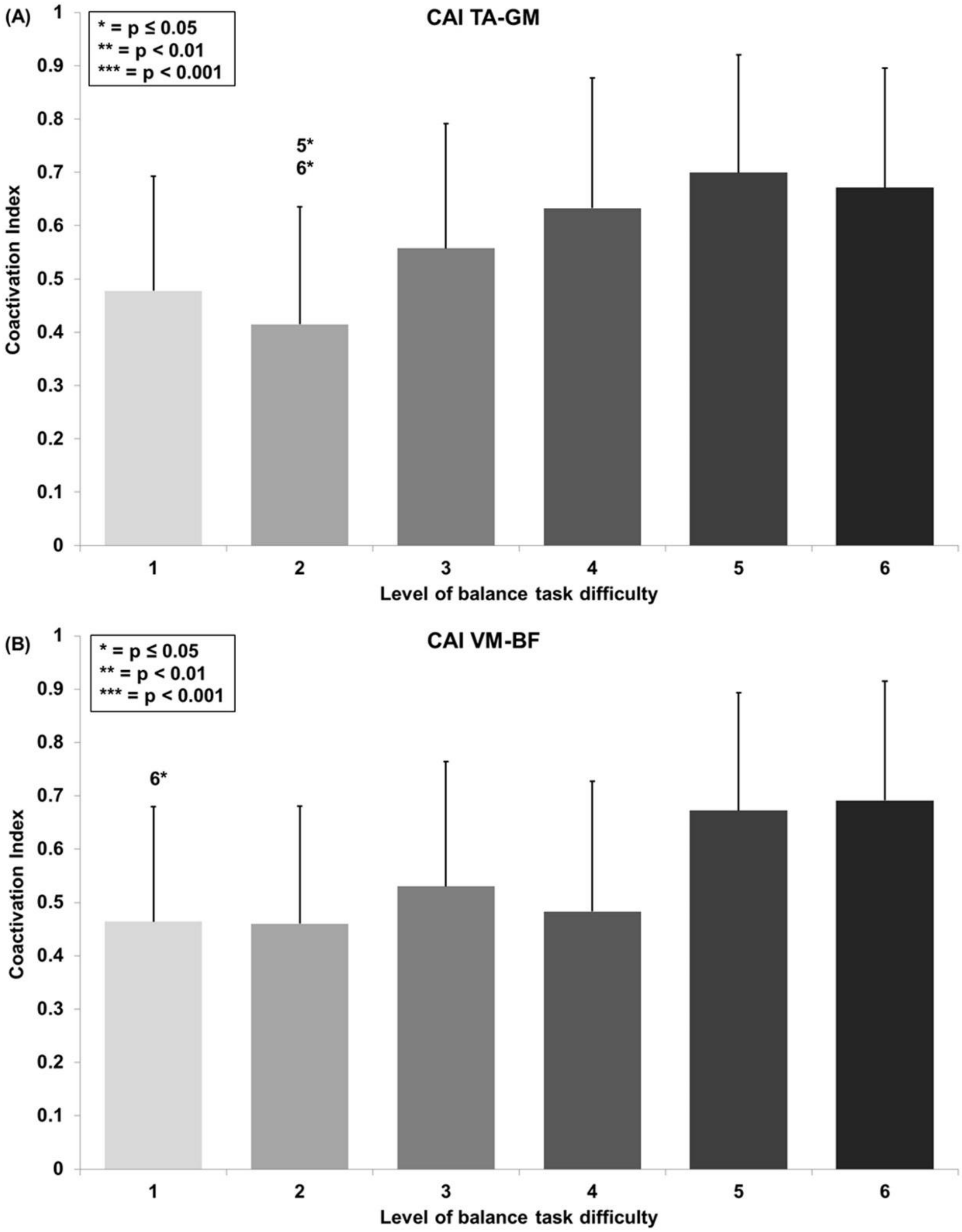

Figure 5 Coactivation Index (CAI) values with standard deviation for the (A) tibialis anterior (TA) and gastrocnemius medialis (GM) and (B) the vastus medialis (VM) and biceps femoris (BF) and all six levels of balance task difficulty. Significant differences between levels are indicated by level number with respective asterisks according to the p-values defined in the legend.

Effects of balance task difficulty on lower limb muscle coactivation

RmANOVA revealed a large main effect for BTD on lower limb muscle coactivation ($F_{(2.9,\ 34.6)}$ = 6.0, p = 0.002, d = 1.41) in terms of the CAI for muscles encompassing the ankle (TA-GM). Bonferroni-corrected pairwise comparison showed significant differences in muscle coactivation (Figure 5A) dependent of BTD between level 2 and 5 (p = 0.016, d = 1.39) as well as between level 2 and 6 (p = 0.022, d = 1.25).

Thigh CAI (VM-BF) showed a large main effect for BTD ($F_{(2.9,\ 35.0)}$ = 5.2, p = 0.005, d = 1.32) as well. Post-hoc pairwise comparison with corrected level of significance for multiple comparison showed significant differences in muscle coactivation (Figure 5B) dependent on BTD between level 1 and 6 (p = 0.035, d = 1.02).

Relationship between postural sway and lower limb muscle activity

The forward multiple regression analysis for the muscles sets of ankle and thigh muscles revealed a single best model ($F_{(1,\ 77)}$ = 38.6, p < 0.001) with the ankle muscles as best predictor for the CoP displacements when level of difficulty increases (Figure 6A). All ankle muscles taken together (TA, PL, and GM) explained 33.7% of the variance (r = 0.580, r^2 = 0.337) of the level-dependent increasing CoP displacements. Examining single muscles and muscle sets (i.e. TA & PL, TA & GM, PL & GM) encompassing the ankle, regression analysis also identified a single best model ($F_{(1,\ 77)}$ = 36.6, p < 0.001). The model identified the TA (Figure 6B) as best predictor explaining 32.5 % of the CoP displacements variance (r = 0.570, r^2 = 0.325). We additionally adjusted the regression analysis for potential confounders such as body height and body mass. Of note, the inclusion of these variables in our analyses did not have an impact on our findings regarding all ankle muscles ($F_{(5,\ 77)}$ = 8.2, p < 0.001; r = 0.603, r^2 = 0.364) and the TA ($F_{(5,\ 77)}$ = 7.6, p < 0.001; r = 0.588, r^2 = 0.346).

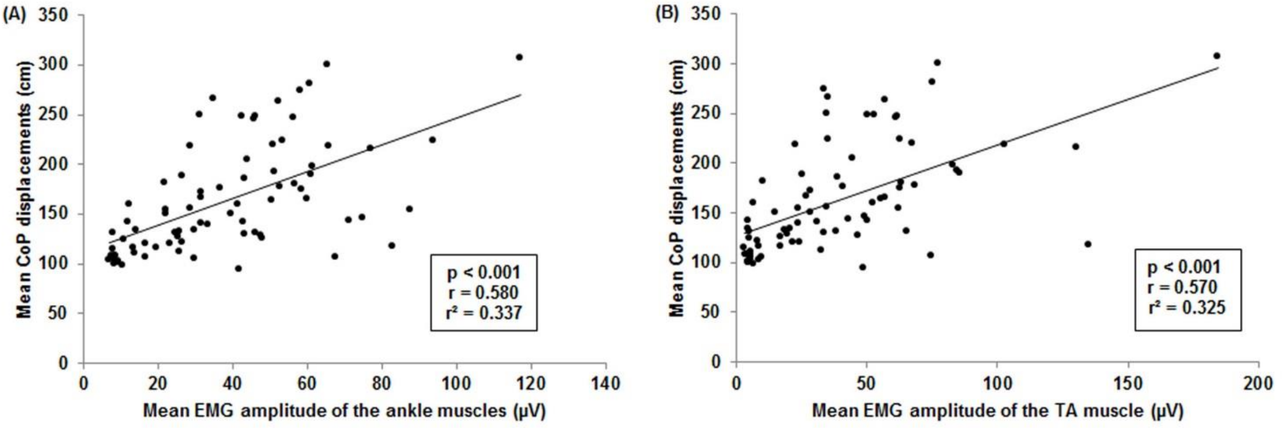

Figure 6 Visualization of the interrelationship between mean center of pressure (CoP) displacements and muscle activity. (A) Interrelation between mean CoP displacements and mean ankle muscle activity of the tibialis anterior (TA), gastrocnemius medialis and peroneus longus. (B) Interrelation between mean CoP displacements and mean muscle activity of the TA. Each point represents mean CoP displacements and mean muscle activity of one participant at a single level of BTD.

DISCUSSION

This is the first study to investigate the specific effects of a gradually increasing BTD on postural sway, lower limb muscle activity and coactivation in healthy adolescents. The main findings of this study were that an increase in the level of BTD results in an increase of postural sway and lower limb muscle activity and coactivation. Furthermore, results support the notion that at first the ankle muscles are responsible for compensating perturbations of a continuously increasing BTD.

Effects of balance task difficulty on postural sway

In general, the observed increase in postural sway with higher levels of BTD is consistent with findings in the literature in adults (Amiridis et al., 2003; Muehlbauer et al., 2012; Cimadoro et al., 2013).. However, none of these studies examined the effects of an increasing BTD on postural sway by only reducing the BoS of a balance board while keeping the other environmental conditions constant. Muehlbauer et al. (2012), for instance, investigated CoP displacements in healthy young adults standing in four different stances (i.e., bipedal, step, tandem, unipedal) and concomitant manipulation of sensory inputs (i.e., vision, surface). The authors reported increased postural sway with reducing the BoS and sensory information. Similar findings on balance performance in were reported by Donath et al. (2016) who compared postural sway of healthy young and old adults performing a single leg stance on different surfaces with open or closed eyes. The authors were able to demonstrate that an increase in task difficulty results in increasing postural sway both within and between young and old adults. When compared to our findings in adolescents, absolute CoP displacements in young adults reported by Muehlbauer et al. (2012) and Donath et al. (2016) were considerably smaller in all conditions (firm surface/eyes opened, foam surface/eyes opened, firm surface/eyes closed) of bipedal and step stance. Although the modulation of BTD was slightly different, the magnitude in performance difference suggests that the effects of BTD on postural sway in adolescents might not be comparable to those in adults. Further, in a recent study, Cimadoro et al. (2013) examined the effects of varying bases of support on postural sway in healthy young adults. Participants performed a single leg stance on three different balance boards. The authors reported higher variability of the CoP position when the balance boards’ BoS was smaller. They interpreted this variability as a decline in balance performance due to higher level of difficulty and concluded that the level of BTD could be easily increased by reducing the balance boards’ BoS. Our findings substantiate this conclusion since the systematic increase in BTD by reducing the BoS resulted in a graded increase in postural sway across all six levels. Finally, increases in postural sway with increasing BTD indicate that the used balance board seems to be well-suited to progressively increase BTD in balance training.

Effects of balance task difficulty on lower limb muscle activity

In terms of muscle activity, our results reveal an increase of the mean muscle activity across the individual muscles (i.e., TA, GM, PL, VM, BF) as well as across the aggregated ankle (TA, PL, and GM) and thigh (VM, and BF) muscles when systematically increasing BTD. Previous research indicated that standing on unstable surfaces (i.e., wobbleboard, swiss ball) results in increased lower limb muscle activity (Wahl and Behm, 2008). In this context, Borreani et al. (2014) examined the influence of different levels of stability on ankle muscle activity. Results indicated an increase in ankle muscle activity with higher levels of instability. These findings were further substantiated by Donath et al. (2016) who reported increases in relative muscle activity in individual ankle (TA, soleus, GM, PL) and thigh muscles (VM, vastus lateralis, BF, semitendinosus) during five balance tasks with varying level of task difficulty. In line with previous studies, our result support the notion that increasing BTD leads to concomitant increases in ankle and thigh muscle activation. Besides the level dependent increases of the CoP displacements, increases in ankle and thigh muscle activity might be explained by the reduced BoS at higher levels. Findings for increased ankle muscle activity are consistent with those of Soderberg et al. (1991), Dohm-Acker et al. (2008), and Cimadoro et al. (2013). These authors reported increased ankle muscle activity in the TA, GM, and PL with increasing BTD in single leg stance. This indicates the high involvement of the ankle muscles when maintaining balance under varying demands to the postural system. Additionally, thigh muscle activity also increased when level of difficulty was increased. The level-dependent elevation of the thigh muscle activity followed a similar pattern but with smaller mean amplitude compared to those of the ankle muscles. Dohm-Acker et al. (2008) reported that EMG activity of the thigh muscles (VM and m. semimembranosus) in single leg stance remained on a steady level when BTD increased. These findings seem to be in contrast with ours. The differences could be explained by the high degree of difficulty of the balance task chosen by Dohm-Acker and colleagues (2008). Provided that a progressive increase in BTD is achieved by reducing the BoS, the single leg stance on an unstable surface (e.g., balance board) would be ranked on the upper end of the BTD continuum. Consequently, thigh muscle activity was increased - irrespective of the chosen unstable surface - to the point where no further increase could be observed. Taken together, the results of the present study and of Dohm-Acker et al. (2008) suggest that thigh muscle activity seems to increase until a certain level of BTD is reached and then plateaus. Further, it might be speculated that an additional increase in trunk muscle activity could have been found with increasing BTD due to changes in the postural strategy (i.e., from ankle to hip strategy) as reported by Donath et al. (2016). This assumption becomes even more apparent when looking at lower limb muscle coactivation data. Moreover, we concur with the conclusion of Dohm-Acker et al. (2008) that the thigh muscles are less involved in fine adjustments responsible to maintain or recover balance after small perturbations compared to the ankle muscles as our results also showed considerably higher activity levels. However, as the magnitude of balance perturbations increases, contributions of the thigh muscles to fine adjustments increase similarly due to a potential shift from the ankle to the hip strategy (Horak and Nashner, 1986). Ultimately, the used balance board is adequate for a continuous progression of BTD in balance training as indicated by the observed increases of lower limb muscle activity from lowest to highest level.

Effects of balance task difficulty on lower limb muscle coactivation

Coactivation of the leg muscles is influenced by a number of variables. It has been shown that with increasing age (Hortobágyi and DeVita, 2000; Benjuya et al., 2004; Donath et al., 2015; Iwamoto et al., 2017; Kurz et al., 2018) and movement velocity (Hortobagyi et al., 2009; Iwamoto et al., 2017) muscle coactivation also elevates in muscles encompassing the ankle and knee joints. In the present study, we investigated how an increase in BTD affects the coactivation of the muscles surrounding ankle and knee joints in healthy adolescents. In our study CAI values obtained for the ankle joint muscles were higher than those reported for young adults in double leg stance on unstable ground by Donath et al. (2016). These differences suggest that ankle muscle activation in adolescents and young adults is not comparable. Additionally, the CAI for muscles encompassing the knee joint showed similar values to those of young adults (Donath et al., 2016). The significant increases observed in the CAI for TA-GM and VM-BF with increasing BTD suggest that higher postural demands result in joint stiffening. Stiffening of the joints can be a mechanism to obtain more postural stability by compensating through a reduction in flexibility and mobility (Benjuya et al., 2004; Donath et al., 2016). The present findings for the ankle CAI (TA-GM) are similar to those of Iwamoto et al. (2017). The authors reported an increase of coactivation of the ankle muscles (TA and soleus) in healthy young adults when performing a balance task with higher movement velocity. Increases in coactivation of the TA and soleus were interpreted as a strategy to provide more postural stability by higher ankle joint stiffness. Further, our results indicate that the CAI (TA-GM) increase from low (level 2) to high levels (level 5 and 6) of BTD. The progressive increase of the CAI seems to be graded, even though our analyses did not yield statistical evidence for this assumption. However, the CAI for muscles encompassing the knee (VM-BF) was especially elevated for high levels (levels 5 and 6) and reached statistical significance at level 6 of the balance task. As the CAI can be used as an indicator for joint stiffening, our data suggest that low-to-medium levels of task difficulty can be compensated for using the ankle strategy. When BTD further increases, increased levels of CAI are needed to stiffen lower limb joints in order to maintain postural stability. These findings indicate that a shift from the ankle to the hip strategy occurred with increasing levels of BTD (Donath et al., 2015). In this context, recent studies (Papegaaij et al., 2016; Watanabe et al., 2018b; a) demonstrated that an increase in postural challenge resulted not only in a change of postural strategy but also in an increase of cortical control. For example, Papegaaij et al. (2016) found decreases of soleus EMG suppression induced by transcranial magnet stimulation only in a balance task with high postural challenge. Therefore, the authors assumed that these changes were related to modulation in intracortical circuits indicating increased cortical control with higher postural demands. Further, Watanabe et al. (2018) reported that coherence in the delta-band between bilateral homologues muscles (e.g., GM-GM) and in the beta-band between unilateral muscles (GM-soleus) changed with increasing postural challenge in young but not old adults. Their results indicate a shift from bilateral synchronous to unilateral cortical control of the ankle muscles as unilateral cortical control increases when postural demands increase. Further, they assumed that this modulatory ability is impaired with increasing age as there were no changes in older adults. When related to the results of present study, these findings suggest a shift from subcortical to cortical control processes with increasing level of BTD which might also result in increased cortical activity. In conclusion, the increase of the CAIs and the assumed change of postural strategy from ankle to hip strategy indicate higher demands to the postural control system which may also result in changes of cortical control and activity. Thus, increases in CAI values are another indicator that BTD can be progressively increased in balance training by the tested balance board.

Relationship between postural sway and lower limb muscle activity

Results of the regression analyses suggest that for the tested balance board and levels of task difficulty the strongest contributions on the muscular level for maintaining postural control were made by the ankle muscles and especially by the TA. These findings support the notion that muscle activity and postural sway are interrelated (Gatev et al., 1999; Watanabe et al., 2018a; b). Tilting movements mainly performed in the anterior/posterior (AP) direction to recover balance (Cimadoro et al., 2013) might explain TA activity as main contributor to CoP displacements although the used balance board was a multi-directional board. Additionally, due to the anatomy of the foot, the leverage in AP direction is larger and enables a more controlled force transduction to the balance board making it easier to maintain and recover the balance board in a horizontal position. Therefore, the relationship found in the present study might not only rely on compensatory mechanisms to increase stability (i.e., stiffening of the ankle joints by increasing co-activation) but also on voluntary contractions to actively control the tilt of the balance board. However, the TA may not only be responsible for dorsi-extension of the ankle but may also be involved in compensatory movements in medio-lateral direction. Activity of the TA may therefore be much more prominent than the PL and GM even if the AP direction is the preferred one to control a multidirectional balance board in bipedal stance. Nevertheless, contributions of the TA to compensatory medio-lateral movements might be limited to bipedal stance. In this context, Watanabe et al. (2018a) analysed the relationship between CoP sway and EMG activity of the GM, gastrocnemius lateralis, and soleus in bipedal as well as unipedal stance and found that these muscles are only involved in medio-lateral sway during unipedal stance. However, the authors did not include they TA in their analyses. Therefore, assumptions on basis of the present results on the contributions of the TA to compensatory medio-lateral movements remain speculative.

Limitations

Few potential limitations of this study warrant discussion. First, additional recordings of kinematic data (e.g., knee angle) and trunk muscle activity might have provided clearer evidence for occurred changes in the postural strategy. Further, this might have helped to elucidate how the more proximal muscles of the trunk (e.g. m. multifidus lumborum and m. internal oblique) are affected by higher levels of task difficulty (Donath et al., 2016). Therefore, our discussion on that subject remains speculative. Moreover, future studies should include the soleus muscle to examine the plantarflexor function irrespective of knee joint motion. In addition, recent studies (Papegaaij et al., 2016; Watanabe et al., 2018b; a) demonstrated increases in cortical control of posture with increasing postural demands. It is hypothesized that increased BTD might be reflected in a shift from subcortical to cortical control processes to maintain balance. Thus, future studies need to elucidate cortical activity during the performance of balance tasks with increasing difficulty using for instance electroencephalography. As the experiment was part of a larger experimental setup, the additional application of kinematics and electrode locations on the trunk would have been too strenuous for the participants. Since we examined adolescents, we tried to keep the preparation phase as short as possible in order to keep the participants as focused and motivated as possible. Finally, future studies should investigate how sex and parameters like the Body Mass Index moderate balance performance with increasing task difficulty.

CONCLUSION

It has previously been shown in healthy adults that the manipulation of the BoS and sensory inputs induces increasing postural demands and muscle activity. The present study is the first to examine the effects of a continuous increase in BTD on postural sway, lower limb muscle activity and coactivation in healthy adolescents. In summary, our findings revealed increased postural sway, muscle activity and coactivation with a continuous increase in BTD in healthy adolescents. Further, our results indicate an interrelationship between postural sway and lower limb muscle activity with increasing postural demands.it can be suggested that compensatory mechanisms which regulate and maintain postural stability are mainly located at the ankle but may shift to the hip with increasing level of BTD. Moreover, the findings provide evidence that the tested balance board can be used to gradually increase BTD in balance training. These insights might be helpful to optimize individual balance training regimes in the fields of rehabilitation and athletic development. While the difficulty-dependent effects on balance performance and neuromuscular activity were demonstrated, it remains unclear how increasing postural demands affect brain activity. Hence, future studies should investigate the effects of gradually increasing BTD on cortical activity in healthy adolescents.

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Conflict of interest

The authors declare that there are no conflicts of interest, financial or otherwise.

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Publication III

BALANCE TASK DIFFICULTY AFFECTS POSTURAL SWAY AND CORTICAL ACTIVITY IN HEALTHY ADOLESCENTS

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Abstract

Electroencephalographic (EEG) research indicates changes in adults' low frequency bands of frontoparietal brain areas executing different balance tasks with increasing postural demands. However, this issue is unsolved for adolescents when performing the same balance task with increasing difficulty. Therefore, we examined the effects of a progressively increasing balance task difficulty on balance performance and brain activity in adolescents. Thirteen healthy adolescents aged 16-17 years performed tests in bipedal upright stance on a balance board with six progressively increasing levels of task difficulty. Postural sway and cortical activity were recorded simultaneously using a pressure sensitive measuring system and EEG. The power spectrum was analyzed for theta (4-7 Hz) and alpha-2 (10-12 Hz) frequency bands in pre-defined frontal, central, and parietal clusters of electrocortical sources. Repeated measures analysis of variance (rmANOVA) showed a significant main effect of task difficulty for postural sway ($p<0.001$; $d=6.36$). Concomitantly, the power spectrum changed in frontal, bilateral central, and bilateral parietal clusters. RmANOVAs revealed significant main effects of task difficulty for theta band power in the frontal ($p<0.001$, $d=1.80$) and both central clusters (left: $p<0.001$, $d=1.49$; right: $p<0.001$, $d=1.42$) as well as for alpha-2 band power in both parietal clusters (left: $p<0.001$, $d=1.39$; right: $p<0.001$, $d=1.05$) and in the central right cluster ($p=0.005$, $d=0.92$). Increases in theta band power (frontal, central) and decreases in alpha-2 power (central, parietal) with increasing balance task difficulty may reflect increased attentional processes and/or error monitoring as well as increased sensory information processing due to increasing postural demands. In general, our findings are mostly in agreement with studies conducted in adults. Similar to adult studies, our data with adolescents indicated the involvement of frontoparietal brain areas in the regulation of postural control. In addition we detected that activity of selected brain areas (e.g., bilateral central) changed with increasing postural demands.

Keywords: Balance, postural control, EEG, theta, alpha-2, ICA, youth

INTRODUCTION

Postural control requires the complex interaction of different structures within the somatosensory system to maintain and recover balance during the performance of sport and everyday activities. Several electroencephalographic (EEG) studies provide evidence that postural control involves the activity of cortical structures under static (e.g., unperturbed/perturbed upright stance) (Edwards et al. 2018; Hülsdünker et al. 2015a; Hülsdünker et al. 2015b; Peterson & Ferris 2018; Slobounov et al. 2009; Solis-Escalante et al. 2019; Varghese et al. 2014) and dynamic conditions (e.g., unperturbed/perturbed walking) (Peterson & Ferris 2018; Sipp et al. 2013; Wagner et al. 2016, for a review see Wittenberg et al. 2017). Most of these studies observed altered activation that contributed to postural control across different cortical areas located near anterior cingulate, dorsolateral prefrontal cortex, supplementary motor areas, parietal, and temporal cortices on either the channel (Edwards et al. 2018; Hülsdünker et al. 2015a; Hülsdünker et al. 2015b) or the source level (Peterson & Ferris 2018; Sipp et al. 2013; Solis-Escalante et al. 2019; Wagner et al. 2016). It has been shown that the application of perturbation impulses during standing and walking results in immediate power increases within the delta (1-3 Hz), theta (4-7 Hz), alpha (8-12 Hz), beta (13-24 Hz), and gamma (30-50 Hz) frequency bands (Peterson & Ferris 2018; Sipp et al. 2013; Slobounov et al. 2009; Solis-Escalante et al. 2019; Varghese et al. 2014). The broadband increment in power is presumably related to cortical processes responsible to detect postural threats. Moreover, Solis-Escalante et al. (2019) reported that broadband power increases were accompanied by concomitant multifocal increases in theta frequency band power. Accordingly, the current state of postural stability/instability could be reflected in the activity level of a cortical network that is involved in postural control (Solis-Escalante et al. 2019; Varghese et al. 2019). There is evidence that changes in the EEG power spectrum due to postural instability occur predominantly in the theta and alpha frequency bands. While previous studies established connections between theta frequency dynamics in fronto-central areas and attentional (Klimesch 1999; Sauseng et al. 2010) as well as cognitive control processes (Anders et al. 2018; Cavanagh and Frank 2014), progression in task-difficulty and postural stability/instability have also been associated with increased theta frequency band power in frontal and parietal cortical areas (Edwards et al. 2018; Hülsdünker et al. 2015a; Hülsdünker et al. 2015b; Sipp et al. 2013; Varghese et al. 2015). In fact, Sipp et al. (2013) and Hülsdünker et al. (2015a) proposed that an increased fronto-central theta band power might be indicative of a postural error detection system that monitors postural stability/instability and initiates adaptive postural responses in situations of high postural instability to maintain or regain balance. In this context, Sipp et al. (2013) hypothesized that theta frequency band activity could be involved in the transfer of sensory information during the performance of postural demanding tasks. In support of this argument, studies that examined cortical activity during beam walking (Sipp et al. 2013) or the performance of different balance tasks with increasing difficulty level (Del Percio et al. 2009; Edwards et al. 2018; Hülsdünker et al. 2015b) reported a strong reactivity of the alpha frequency band in terms of decreases in power , particularly in parietal areas. While widespread fluctuations in the alpha-1 frequency band (8-10 Hz) are supposed to reflect global processes of attention and alertness (i.e., power decrease), as well as idling (i.e., power increase) (Smith et al. 1999), activity within the alpha-2 frequency band (10-12 Hz) appear to be associated with sensory and movement-related information processing (Leocani et al. 1997; Pfurtscheller et al. 1996). More specifically, there is evidence of altered alpha-2 frequency band power that is associated with task-specific cortical information processing and communication between frontal and parietal cortical structures (Bazanova and Vernon 2014).

Of note, balance task difficulty can primarily be increased by diminishing the sensory input (e.g., eyes opened/closed), by reducing the base-of-support (e.g., bipedal vs monopedal stance), by changing the characteristics of the surface (e.g., stable/unstable), or a combination of these modalities. Considering the variety of modifying factors, it is difficult to establish how these multimodal factors contribute to task difficulty. Previous research (Edwards et al. 2018; Del Percio et al. 2009; Hülsdünker et al. 2015a; Hülsdünker et al. 2015b; Tse et al. 2013; Varghese et al. 2015) examined the effects of performing continuous balance tasks of varying difficulty levels on cortical activity. However, these studies either modified sensory input, base-of-support, and surface characteristics (Edwards et al. 2018; Hülsdünker et al. 2015a; Hülsdünker et al. 2015b; Tse et al. 2013) or they reduced the base-of-support by changing the stance position (Del Percio et al. 2009; Varghese et al. 2015). In other studies (Dohmacker et al. 2008; Ciamadoro et al. 2013) that changed the base-of-support only, this was done using different balance exercise tools (e.g., sissles, balance pads etc).The use of different exercise equipment may cause bias because the experiment is not standardized and controlled for this factor. Therefore and in an attempt to elucidate the effects of balance task difficulty, one single factor should be addressed per study (i.e., manipulation of base-of-support OR sensory input). Moreover, if base-of-support is manipulated it should be done using one standardized balance exercise tool while all other modalities including sensory input are kept constant. Accordingly, changes in cortical activity can solely be attributed to the systematic manipulation of base-of-support. Since scalp electrodes record a mixture of activity from distinct brain areas, the localization of these sources is mathematically undetermined (Nunez and Srinivasan 2006). Signal processing techniques such as independent component analyses (ICA) have the potential to identify maximally independent sources of functional brain dynamics. Previous studies have shown that ICA is applicable even during whole body movements such as walking or running (Gwin et al. 2010; Wagner et al. 2016). Hence, source space analyses may provide a deeper insight into the activation of cortical areas with increasing instability and postural demands. Additionally, the aforementioned studies investigated only adult populations. As the brain (Arain et al. 2013) still matures during adolescence, it is uncertain whether posture-related brain activity in adolescents follows similar patterns as reported in the adult literature. Moreover, information on neurophysiological mechanisms related to postural control are hardly available for youth (Gebel et al. 2020). However, knowledge on the underlying neurophysiological correlates of postural control in youth are needed to design and develop balance training programs for the general youth population and for young athletes. Therefore, more research is needed with adolescents to elucidate frequency characteristics of cortical activity during the performance of balance tasks with increasing task difficulty.To the authors' knowledge, there are currently no studies available that investigated how a graded increase in balance task difficulty affects cortical activity in a healthy youth population.

Therefore, the objectives of this study were to examine the effects of a gradual increase in balance task difficulty (only by changing the base of support) on postural sway and frequency band power by means of ICA-based source space analyses in healthy adolescents. Based on the relevant literature, we expected that increasing postural demands result in increased postural sway (Muehlbauer et al. 2012) and in changes of cortical activity in frontal, central, and parietal areas (Edwards et al. 2018; Hülsdünker et al. 2015a; Hülsdünker et al. 2015b; Sipp et al. 2013; Slobounov et al. 2009). We further hypothesized that progression in task difficulty (i.e., reduced base-of-support) results in a concomitant increase in theta frequency band power in frontal and central areas. Of note, there is evidence that these regions of interest adopt attentional and error-related feedback processes (Hülsdünker et al. 2015a; Sipp et al. 2013; Slobounov et al. 2009; Varghese et al. 2014). Simultaneously, increasing postural demands may result in increased sensory processing reflected by decreased alpha-2 frequency band power in centro-parietal regions (Hülsdünker et al. 2015b).

MATERIALS AND METHODS

Participants

Based on the large main effect ($\eta^2 = 0.59$) of base of support on theta frequency band power reported by Hülsdünker et al. (2015b), an a priori power analysis with G*Power (Version 3.1.9.2, University of Kiel, Germany) using a single group repeated measures analysis of variance (rmANOVA) design with 7 levels (baseline and 6 levels of task difficulty) was calculated. The analysis revealed that a total sample size of N = 8 would be sufficient to find significant and large-sized main effects of difficulty level (effect size $f = 0.4$, $\alpha = 0.05$, power = 0.80), with an actual power of 0.85 (critical F-value = 2.32). A physical education class including 13 (3 female / 10 male) healthy high-school students aged 16-17 years volunteered to participate in this study. Anthropometrics as well as the results on postural sway and electromyographic activity of the leg muscles have been reported previously (Gebel et al. 2019). The EEG data presented in this article were recorded in the same study using the same study design. All participants and their legal guardians gave their written informed consent prior to the onset of the study. The study was approved by the local ethics committee of the University of Potsdam (application no. 18/2017) and conducted according to the latest version of the Declaration of Helsinki.

Experimental procedure

A single group repeated measures design was used to examine the effects of increasing balance task difficulty on postural sway and cortical activity in healthy adolescents. For this purpose, participants attended the biomechanics laboratory for a single experimental session. Every session started with a standardized familiarization to introduce the multidirectional balance training device (balance board) and its six difficulty levels. Thereafter, participants performed three sets of six balance tasks. Each set consisted of a randomized order of the six levels of balance task difficulty. Overall, testing of one participant comprised 18 trials (3 × level 1-6) with each trial lasting 30 s per level. Continuous EEG activity was recorded during every trial while participants performed respective balance tasks on the balance board. Further, we recorded a separate 3 min EEG baseline condition during quiet bipedal stance prior to the first set and another separate baseline measure after the third set. Anthropometric data (i.e., body height and body mass) were assessed using a stadiometer (seca 213, seca Gmbh, Hamburg, Germany) and a bioimpedance analysis system (InBody 720, BioSpace, Seoul, Korea), respectively.

Balance tasks and balance performance

The applied balance tasks and the testing of balance performance were similar to our previously published study (Gebel et al. 2019). For a more detailed description of the balance tasks and the CoP data analysis, readers are referred to the methods section of Gebel et al. (2019). All balance tasks comprised bipedal upright standing (without shoes) on the balance board. Trials started from a standardized position (i.e., participants held on to a handrail in front of them) which allowed the participants a quiet stance to bring the board in horizontal position. During data recording, participants were instructed to hold their hands akimbo and to fixate their gaze at a cross on a nearby wall (3 m distance). Additionally, participants were instructed to keep the balance board as steady as possible in the horizontal plane and to avoid ground contact with the board's edges during the trials. The progressive increase in balance task difficulty was realized using a commercially available multi-directional balance board (Wobblesmart©, Artzt GmbH, Dornburg, Germany) which allows to tilt in every direction. The pivot attached to the board platform has an integrated mechanism to increase task difficulty. By gradual clockwise rotation, the pivot can be adjusted at six different positions (level 1-6). The change in position elevates the platform progressively from 6.5 cm (level 1) to 8 cm (level 6) and simultaneously reduces the pivots base-of-support from approximately 14 to 4 cm (Fig 1 A-C). During the balance tests on the balance board, postural sway (i.e., absolute CoP displacements in medio-lateral and anterior-posterior direction) was assessed as a measure for balance performance using a pressure sensitive measuring system (Pedar©, novel GmbH, München, Germany). For this purpose, two pressure-sensitive sensor mats (Posturo S2094, novel GmbH, München, Germany) were fixed on the balance board to record CoP trajectories at the maximum sampling rate of 40 Hz using the Posturo 32 Expert software (version 25.3.6, novel GmbH, München, Germany). EEG and CoP data were synchronized at the start of the CoP recordings by sending a continuous 5 V signal from the Pedar© system (Posturo Sync Box, novel GmbH, München, Germany) to the EEG system (Fig. 1D). Absolute CoP displacements provided by the Posturo 32 Expert software were averaged for every participant and each level of task difficulty.

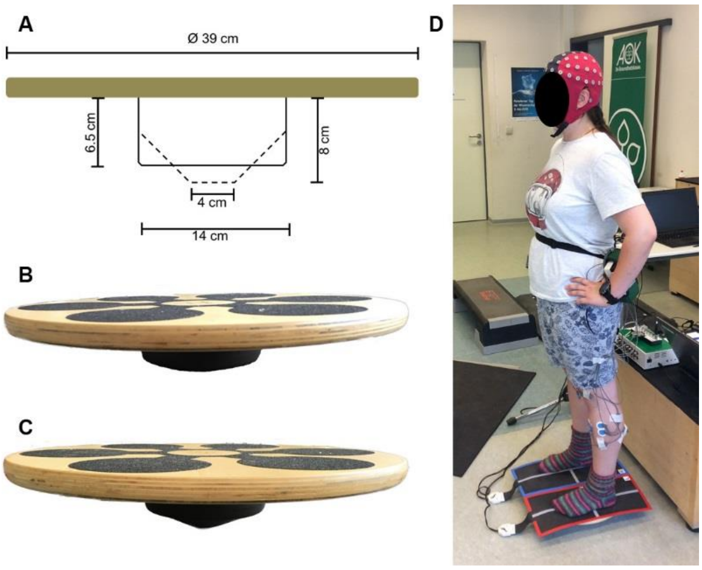

Fig. 1 (A) Schematic representation of the balance board with its mechanically adjustable pivot modified according to Gebel et al. (2019). (B) Balance board with the pivot at level 1. (C) Balance board with the pivot at level 6. (D) Experimental setup

Electroencephalographic (EEG) recordings and analysis

Cortical activity was continuously recorded during each test condition on the balance board. EEG signals were assessed utilizing a mobile EEG system (eego™ sports, Advanced Neuro Technology B.V., Enschede, Netherlands) with 64 Ag/AgCl passive electrodes implemented in an elastic sensor cap (Waveguard classic, Advanced Neuro Technology B.V., Enschede, Netherlands). Electrode positions were set according to the extended 10-20 system of electrode placement. Channels were referenced to the CPz electrode and electrode impedance was kept below 5 kΩ to provide a high signal-to-noise ratio. The analog EEG signals were amplified and then digitized using a 24-bit analog-to-digital converter (eego™ sports, Advanced Neuro Technology B.V., Enschede, Netherlands). Digitized EEG signals were recorded with a sampling frequency of 1,024 Hz using the eego™ software (ANT Neuro eego™, Version 1.6, Neuro Technology B.V., Enschede, Netherlands).

The acquired EEG data were processed offline using MATLAB (Mathworks Inc., Natick, MA, USA) and the EEGLAB 13.5.4b toolbox (Delorme and Makeig 2004). For further analysis, at first line noise was removed with the help of the CleanLine plugin (Mullen 2012). Thereafter, physiological signals were band pass filtered with a finite impulse response filter ranging from 3 to 30 Hz and finally down-sampled to 256 Hz. Channels with electrode movement artefacts, non-stereotypical electromyographic activity and bad scalp contact were manually removed upon visual inspection. Thereafter, EEG data were re-referenced to common average. Typically, we had to discard 10 channels (± 3) per participant. Continuous data were visually inspected and the identified non-stereotypical artifacts were removed from the data set. Furthermore, data points before and after trigger onset/offset were removed. An adaptive mixture ICA (Palmer et al. 2011) was performed on the remaining data to extract spatio-temporal features of cortical activity for each participant and to identify stationary and maximally independent components (IC) (Makeig et al. 1996). Further, an equivalent dipole model for each IC was calculated using a four-shell spherical head model implemented in the DIPFIT toolbox (Oostenveld and Oostendorp 2002). According to the heuristic approach as described by Onton and Makeig (2006), we separated functional activity from stereotypical artifacts. This means that ICs were rated as functional by visual inspection on the basis of the scalp topographic maps, time courses, frequency spectra, and location of the dipole model. ICs that were rated as functional were considered for further analyses. However, ICs with artifacts from electro-oculographic (i.e., eye blinks) sources and muscle electromyographic activities were dismissed. If the single equivalent dipole model of a functional IC revealed more the 15% residual variance from the spherical four-shell head model, the component was also rejected from further analyses. A k-means algorithm was applied to cluster the remaining ICs across all participants. ICs were assigned to a cluster if they were located within two standard deviations of the respective cluster. Clusters that contained components from less than 11 participants (< 80% of the sample) were excluded Overall, 170 ICs were used for cluster analysis with an average of 13 ICs (± 4) per participant. For frequency specific analyses, EEG data were merged for all three trials within a level of task difficulty. This was done for each participant separately. After artefact rejection and IC identification, the average length of the merged trials was 86.2 s (± 6.2 s) per level. Absolute spectral power was calculated for two predefined frequency bands (4-7 Hz [theta], 10-12 Hz [alpha-2]) and for each IC using a fast fourier transformation with a spectral resolution of 1 Hz and a 10% Hanning window. For analyses, absolute spectral power for each frequency band was averaged across individual ICs within the respective clusters.

Statistical analyses

All statistical tests were performed using SPSS (Version 25, IBM, Chicago, IL, USA). Model residuals of CoP and EEG data were tested using the Shapiro-Wilk test to verify normality assumption for repeated measures analyses of variance (rmANOVA). In order to control if balance performance was affected by task difficulty, a single rmANOVA was computed for postural sway (absolute CoP displacements) with the six levels of task difficulty as repeating factors. Further, seven separate rmANOVAs were computed for the absolute spectral power of predefined frequency bands (theta and alpha-2) within the respective clusters. The factor task difficulty comprised six increasing difficulty levels together with baseline measures. If significant main effects of task difficulty were registered for balance performance or cortical activity, post-hoc tests were applied using Bonferroni-corrected paired t-tests. Thus, it was possible to identify differences between single levels of balance task difficulty in both balance performance as well as cortical activity for each cluster. If necessary, the Greenhouse-Geisser correction for non-sphericity was applied. The level of significance was set at $p \leq 0.05$ for all statistical analyses. Effect estimates of partial eta-squared (ηp^2) were converted into Cohen’s d and interpreted according to Cohen (1988) with ≥ 0.2 as small, ≥ 0.5 as medium, and ≥ 0.8 as large effects.

RESULTS

Balance performance

The rmANOVA results for postural sway indicated a significant main effect of task difficulty ($F_{(2.4,\ 29.4)} = 121.6$, $p < 0.001$; $d = 6.36$). Post-hoc tests showed a significant increase in CoP displacements with increasing task difficulty. A more detailed report on the post-hoc results including figures can be found in a previous study (Gebel et al. 2019).

Cortical sources

The k-means clustering algorithm revealed five robust clusters composed of electrocortical sources in frontal ($n_{IC} = 21$, 11 participants), bilateral central (central left $n_{IC} = 22$, 13 participants, central right ($n_{IC} = 32$, 11 participants) and bilateral parietal (parietal left $n_{IC} = 29$, 11 participants, and parietal right ($n_{IC} = 26$, 13 participants) areas (Fig. 2 A-C).

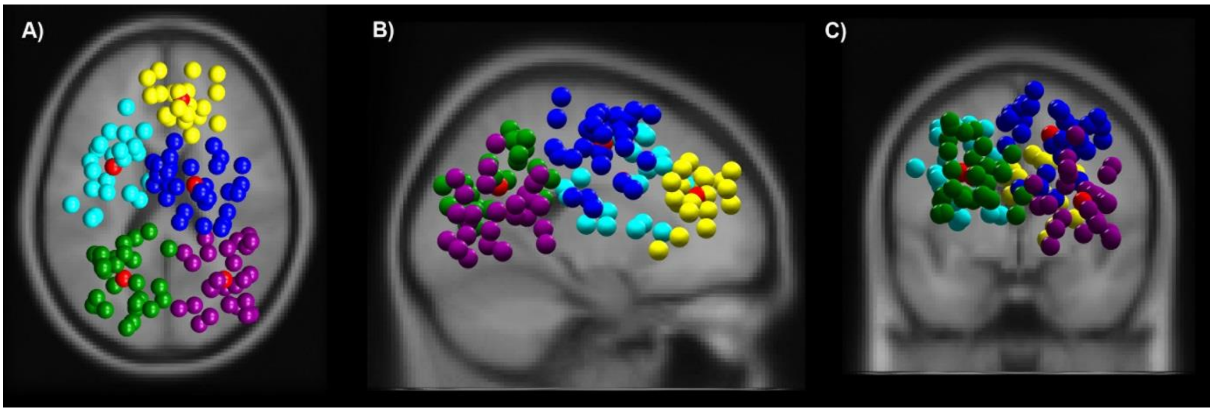

Fig. 2 Clusters of independent component EEG sources localized in frontal (yellow), central left (cyan), central right (blue), parietal left (green), and parietal right (purple) from top (A), sagittal (B), and coronal view (C). Red spheres indicate respective cluster centroids. All other colored spheres indicate a single EEG signal source

Theta frequency band

The rmANOVA revealed a significant large-sized main effect of balance task difficulty for absolute frontal theta frequency band power ($F_{(6,\ 120)} = 16.137$, $p < 0.001$; $d = 1.80$). Post hoc tests identified a significant increase in absolute theta power (Fig. 3). The increment in power was significant between baseline and levels 2 to 6 (all p-values ≤ 0.017), between level 1 and levels 4 to 6 (all p-values ≤ 0.05), between level 2 and levels 5 and 6 (all p-values ≤ 0.023) and between level 3 and level 5 ($p = 0.029$). Effect sizes of the applied post-hoc tests ranged between $d = 0.07$-0.17.

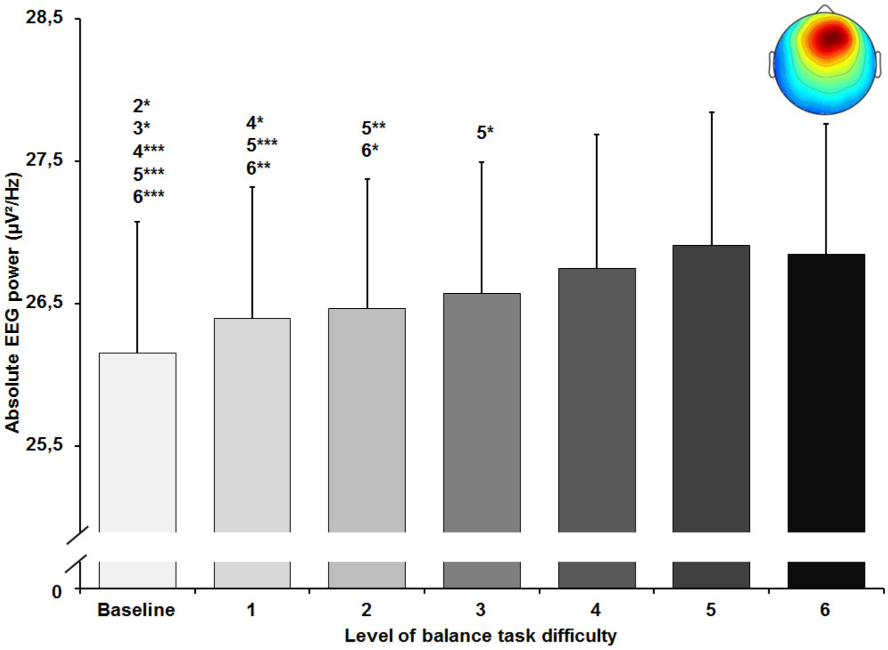

Fig. 3 Absolute theta frequency band power in μV^2/Hz in the frontal cluster (scalp map in the upper right corner) with standard error of the mean across all six levels of balance task difficulty. Significant differences between levels are indicated by level number with respective asterisks; $p < 0.05$*, $p < 0.01$**, and $p < 0.001$***

A significant main effect of task difficulty was found for absolute theta frequency band power in the central left ($F_{(1.84, 38.56)} = 11.594$, $p < 0.001$; $d = 1.49$) and in the central right ($F_{(1.50, 46.64)} = 15.637$, $p < 0.001$; $d = 1.42$) cluster as well. Post-hoc tests revealed significant increases in absolute theta power for the central left cluster (Fig. 4A) between level 6 and all other levels of task difficulty (all p-values ≤ 0.043, $0.09 \leq d \leq 0.31$), except level 4 which differed significantly from level 1 ($p = 0.016$; $d = 0.17$). Significant increments in power were found for the central right cluster (Fig. 4B) between baseline and levels 2 to 6 (all p-values ≤ 0.029, $0.37 \leq d \leq 0.57$), between level 1 and levels 4 to 6 (all p-values ≤ 0.009, $0.13 \leq d \leq 0.22$), as well as between levels 2 to 4 and level 6 (all p-values ≤ 0.012, $0.09 \leq d \leq 0.2$).

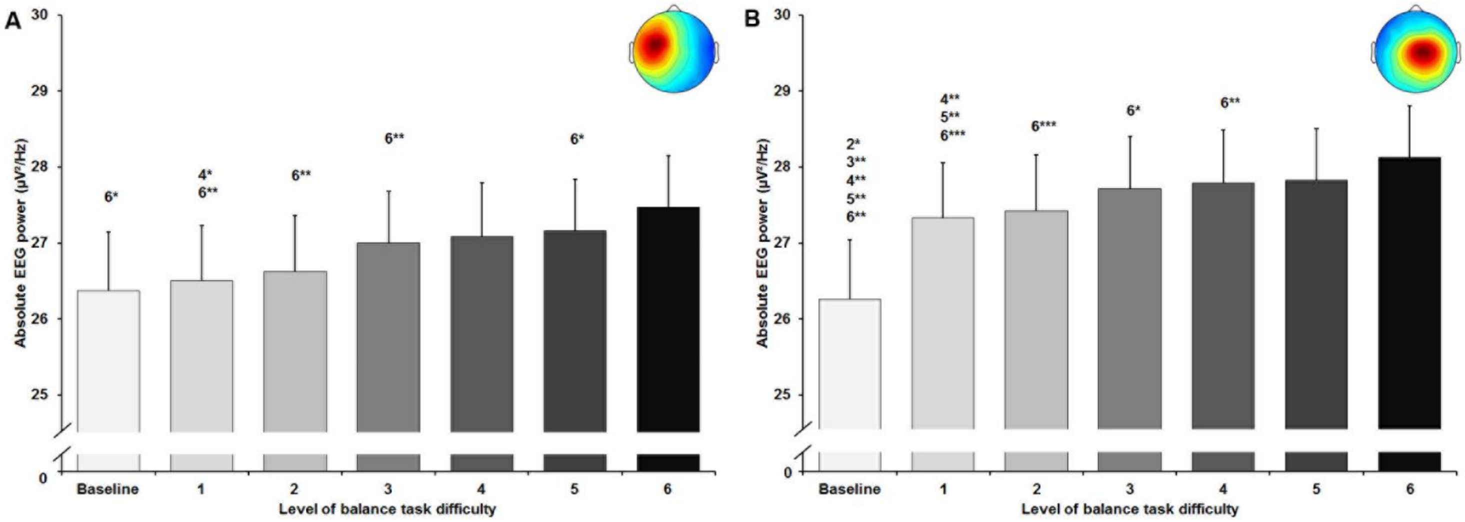

Fig. 4 Absolute theta frequency band power in µV²/Hz in the central left (A) and central right (B) cluster (respective scalp maps in the upper right corner) with standard error of the mean across all six levels of balance task difficulty. Significant differences between levels are indicated by level number with respective asterisks; p < 0.05*, p < 0.01**, and p < 0.001***

Alpha-2 frequency band

The statistical analyses for central brain areas showed a significant large-sized main effect of balance task difficulty for absolute alpha-2 frequency band power in the centralR cluster ($F_{(1.62, 50.15)} = 6.632$, $p = 0.005$; $d = 0.92$). All applied post-hoc tests did not reach the level of significance (Fig. 5A). No significant main effect was found for the centralL cluster ($F_{(1.64, 34.39)} = 2.755$, $p = 0.087$; $d = 0.72$) (Fig. 5B). Further, both clusters in the parietal area showed a significant large-sized main effect of task difficulty for absolute alpha-2 power (parietalL $F_{(2.60, 72.78)} = 13.614$, $p < 0.001$; $d = 1.39$; parietalR $F_{(2.94, 73.38)} = 6.885$, $p < 0.001$; $d = 1.05$). For the parietal cluster (Fig. 6A), post-hoc tests identified significant decreases in power between baseline and levels 1 to 6 (all p-values ≤ 0.003, $0.12 \leq d \leq 0.22$). For the parietalR cluster (Fig. 6B), significant decreases were found between baseline and levels 3 to 6 (all p-values ≤ 0.028, $0.15 \leq d \leq 0.18$).

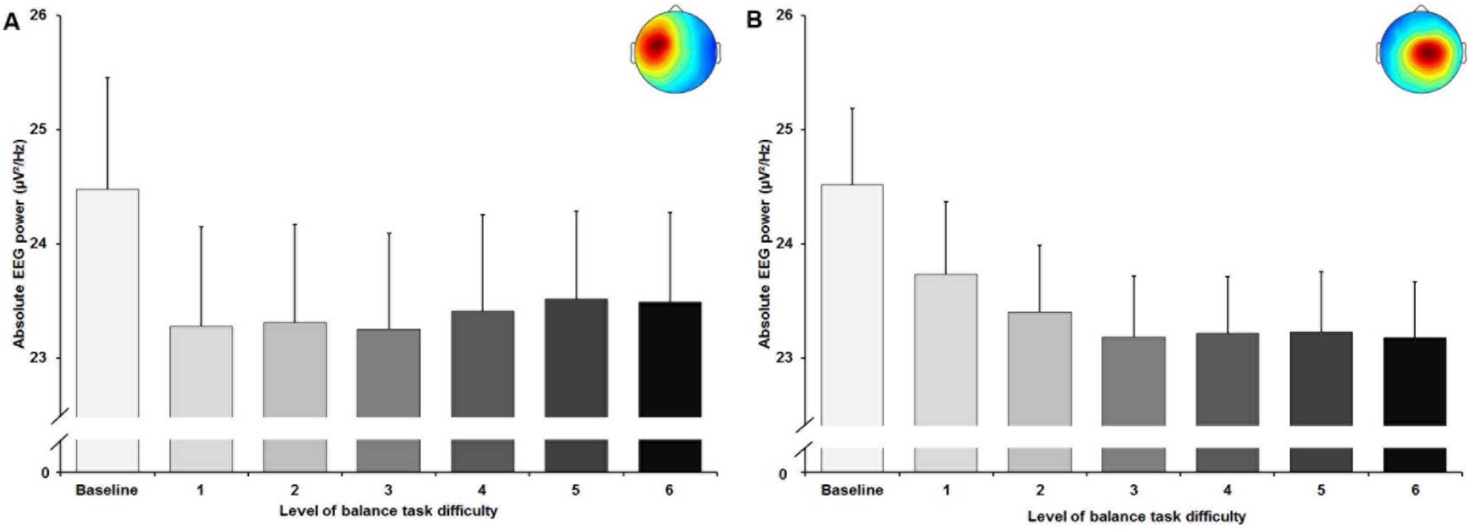

Fig. 5 Absolute alpha-2 frequency band power in µV²/Hz in the central left (A) and central right (B) cluster (respective scalp maps in the upper right corner) with standard error of the mean across all six levels of balance task difficulty. Significant differences between levels are indicated by level number with respective asterisks; $p < 0.05$*, $p < 0.01$**, and $p < 0.001$***

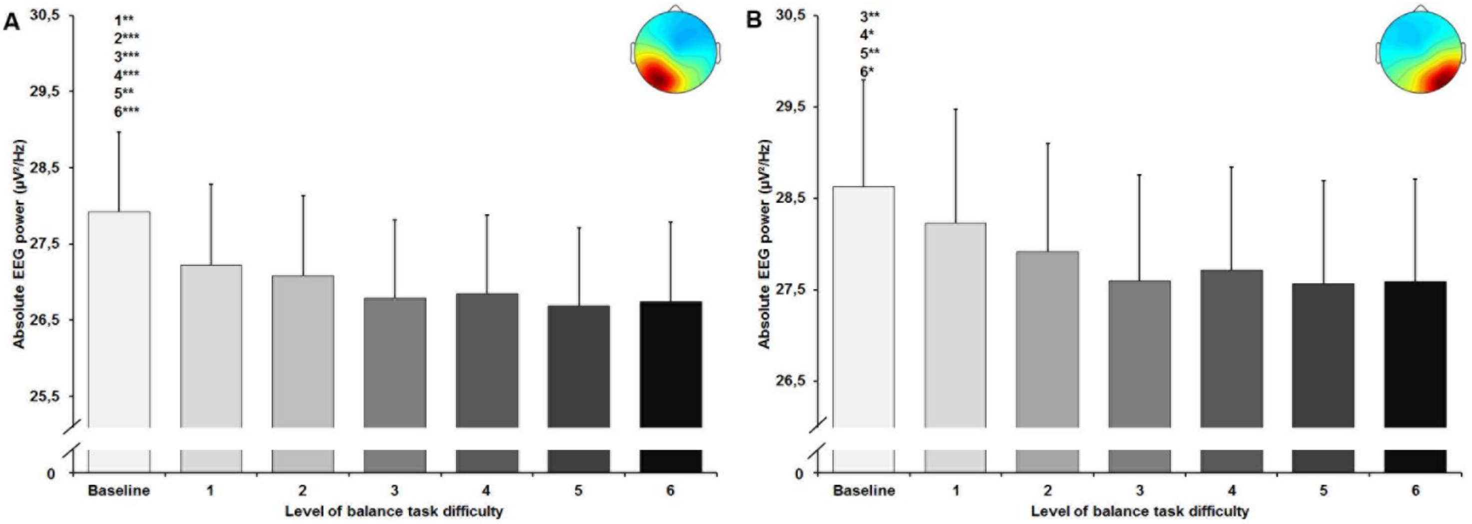

Fig. 6 Absolute alpha-2 frequency band power in µV²/Hz in the parietal left (A) and parietal right (B) cluster (respective scalp maps in the upper right corner) with standard error of the mean across all six levels of balance task difficulty. Significant differences between levels are indicated by level number with respective asterisks; $p < 0.05$*, $p < 0.01$**, and $p < 0.001$***

DISCUSSION

This study is the first to examine cortical activity in the theta and alpha-2 frequency bands using ICA analyses while performing a balance task with a progressively increased task difficulty level in healthy adolescents. The main findings of this study were that postural sway (i.e., CoP displacements) increased and cortical activity changed with increasing balance task difficulty. In terms of cortical activity, theta frequency band power in frontal and bilateral central (left and right) areas increased with increasing balance task difficulty. Further, we found significant decreases in alpha-2 frequency band power with increasing instability in bilateral parietal (left and right) areas. Alpha-2 power in bilateral central areas decreased as well but we observed no significant differences between levels of task difficulty.

Balance performance

In accordance with our hypothesis, we observed increased postural sway when task difficulty increased. Our findings in adolescents are consistent with previous studies (Donath et al. 2016; Muehlbauer et al. 2012) investigating how an increasing balance task difficulty affects balance performance in adults. Donath et al.(2016) as well as Muehlbauer et al. (2012) reported an increase of postural sway with increasing task difficulty in young (Donath et al. 2016; Muehlbauer et al. 2012) and old adults (Donath et al. 2016). In contrast to these studies, which manipulated stance (e.g., bipedal, unipedal) and sensory inputs (i.e., surface, vision), we only reduced the balance boards' base of support to increase task difficulty. Considering the implementation of a progressive increase of task difficulty into a balance training protocol, our results suggest that an increase in task difficulty by reducing the base of support of a balance board has a more continuous slope than manipulating several external conditions (i.e., stance, vision) simultaneously. Further, the reduction of the base of support also has an impact on neuromuscular activity. Using the same study design, Gebel et al. (2019) recently reported that these decreases in balance performance were accompanied by increases in lower limb muscle activity and muscle coactivation. The authors interpreted their findings as a change in the underlying postural strategy caused by increasing postural demands. This statement should be verified in future studies using cortico-muscular coherence analysis.

Theta frequency band

As hypothesized, we found significant increases of theta frequency band power in frontal and central areas with increasing balance task difficulty in adolescents. These findings are consistent with previous studies in healthy adults which observed an increase in theta power over frontal (Hülsdünker et al. 2015a; Hülsdünker et al. 2015b) and central electrode sites (Edwards et al. 2018; Hülsdünker et al. 2015a; Hülsdünker et al. 2015b) during continuous balance tasks with varying degrees of instability. These authors suggested that the increase in theta power over frontal and central electrodes may originate from the anterior cingulate cortex and sensorimotor areas, which are highly involved in processes of error detection and sensory information processing (Slobounov et al. 2009; Varghese et al. 2014). A few other studies reported increases in frontal and central theta power induced by sudden postural perturbations during quiet bipedal stance (Varghese et al. 2014), unipedal stance (Slobounov et al. 2009), and while walking on a balance beam (Sipp et al. 2013). Further, Sipp et al. (2013) showed that walking on a narrow balance beam compared to treadmill walking resulted in increased theta power in cortical sources located near or in anterior cingulate cortex, anterior parietal, dorsolateral prefrontal, and sensorimotor cortex. In this context, attentional processes responsible for successful balance performance under challenging conditions may contribute to increased theta power in frontal areas. Loss of balance appears to be associated with immediate increases in theta power across multiple cortical areas including the anterior cingulate and anterior parietal cortex (Sipp et al. 2013). After balance recovery, activity even decreased below baseline level. These authors hypothesized that the observed increase in theta band activity may act as an error detecting system to initiate situation-specific postural responses. The existence of a balance-specific cortical network has further been supported by findings from Solis-Escalante et al. (2019) who observed increased theta power in the anterior cingulate, prefrontal, posterior parietal, sensorimotor cortex, and supplementary motor area following the application of perturbation impulses during bipedal standing. These authors interpreted the multifocal theta power enhancement as activity of a cortical network that is involved in detecting postural threats and initiating adequate postural responses. Moreover, Varghese et al. (2019) speculated upon the existence of a cortical balance control network. Their assumption was based on widespread topological rearrangements in functional cortical connectivity within delta, theta, alpha, and beta frequency bands during the performance of reactive balance tasks. Our results may point in a similar direction and can be interpreted as activation of a balance control network during the performance of a continuous balance task. Therefore, the continuous increase in theta frequency band power within the frontal and central clusters may reflect a higher information processing load due to increased level-dependent postural demands.

As previous studies in adults, our analyses of the frontal cluster showed no further increase of theta frequency band power in the balance task with highest level of difficulty. This may be referred to as a “ceiling effect” (Edwards et al. 2018; Hülsdünker et al. 2015a), demonstrating no further increase in theta band spectral power when instability becomes excessive and postural demands are too high to maintain balance. But in contrast to Hülsdünker et al. (2015a) and Edwards et al. (2018), we observed this phenomenon only in the frontal cluster and not in both central clusters where theta power further increased in the highest level of balance task difficulty. This “ceiling effect”, restricted to frontal areas, might be also explained by other processes than postural error detection. Findings of numerous studies associated higher frontal theta power with increased attention in cognitive (Smith et al. 1999), visuomotor (Slobounov et al. 2000), complex motor (Baumeister et al. 2008), and sensorimotor tasks (Baumeister et al. 2013). Based on their findings, Smith et al. (1999) as well as Baumeister et al. (2008) suggested that changes in frontal theta power are related to focused attention as well as engagement and effort into a specific task. In this context, observed increases in frontal theta power may indicate increased focused attention and the concomitant activation of additional attentional resources when the difficulty of the balance task increased. However, if the demands of the balance task exceed the individuals’ capability to maintain balance, focused attention and the allocated attentional resources remain at the same level due to consistent task-specific engagement and effort. This suggestion was supported by the fact that at the highest level of difficulty most participants were unable to move the balance board back into the horizontal plane after leaving the start position. Participants tilted the board from edge to edge. Otherwise, this position could have offered more stability for the participants and therefore afforded less attentional resources than balancing on the narrow pivot of the balance board. However, this would arise the question why theta power further increased in sensorimotor areas despite increased stability and decreased sensory information being processed.

Alpha-2 frequency band

In line with our hypothesis, we found reductions in alpha-2 frequency band power in both central and parietal areas at both hemispheres when balance task difficulty increased. Whereas increases in alpha power are considered to reflect inhibitory processes in task-irrelevant brain areas to facilitate information processing in task-relevant areas, decreases in alpha-2 power indicate task-specific information processing (Del Percio et al. 2009; Del Percio et al. 2007; Klimesch et al. 2006; Slobounov et al. 2009). Previous studies reported decreased power in the alpha frequency band with increasing balance task difficulty in electrode-based regions of interest (Edwards et al. 2018; Hülsdünker et al. 2015b). For instance, Hülsdünker et al. (2015b) reported that decreases in alpha-2 power were strongest in centro-parietal areas (CP1, CPz, CP2, P3, Pz, P4) with increasing instability. The authors interpreted their findings as increased sensory information processing caused by compensatory postural movements. Furthermore, Edwards et al. (2018) observed similar alterations in the broad alpha frequency band (8-12 Hz). They reported decreased alpha power over centro-parietal electrode sites (C3, Cz, C4, P3, P4) with increased level of task difficulty and suggested that information processing increased with balance challenge. In addition, results of Sipp et al.(2013) showed decreased frequency band power between 8-12 Hz (alpha-1 and alpha-2) in functional clusters located near sensorimotor cortex of both hemispheres when walking on a balance beam compared to treadmill walking in young adults. In this context and in view of the present results, significant reductions in alpha-2 power, predominantly in bilateral parietal areas, may suggest an incremental functional involvement of both areas in postural control processes with increasing task difficulty and instability. This assumption may be further supported when considering the level-dependent development of the alpha-2 power in both parietal clusters found in the present study. Even though significant differences in alpha-2 frequency band power were only observed between baseline and higher levels of balance task difficulty, alpha-2 power seemed to further decrease from the lowest (level 1-2) to the highest levels (level 5-6) (Figure 7A and 7B). Interestingly, we observed such tendencies between the lowest and highest levels of difficulty not for both central but the central right cluster. As reductions of alpha-2 power in sensorimotor areas were associated with increased processing of sensory and movement-related information (Leocani et al. 1997; Pfurtscheller et al. 1996), present results of decreases in mainly parietal alpha-2 power may indicate increased sensory and movement-related information processing with increasing instability.

Limitations

A methodical limitation of this study is the approach of source space localization by means of only 64 EEG channels. We are aware of the inversion problem when conducting source space analyses. Therefore, results of the ICA-based source space localization should be interpreted with caution since precise localization of cortical activity is only possible with high-density EEG systems, co-registration, and additional functional magnetic resonance imaging. However, as minimal standard source space analyses require at least an EEG system with 64 channels for data acquisition, although precision increases with the number of channels used (Sohrabpour et al. 2015). Further, an ICA does not necessarily separate all relevant components for each participant. It is also possible that multiple ICs from one participant represent a single source and contribute to the same cluster. This may affect the statistical analyses. Here, we used all ICs because we could not rule out that multiple ICs represent a single source but with different time-dependent characteristics. Further, this approach has frequently been used in the literature (Peterson & Ferris 2018; Sipp et al. 2013; Solis-Escalante et al., 2019; Wagner et al. 2016). Currently, there is no consensus on how to deal with this problem. Another limiting or confounding factor might be the continuous visual input throughout the experiment. In contrast to studies of Hülsdünker et al. (2015b) and Edwards et al. (2018) who observed a reduction in alpha-2 power during balance tasks without visual input, the participants in our study performed all balance tasks with eyes opened. Since we kept visual conditions (i.e., gaze fixation at a cross at 3 m distance) constant during every level of balance task difficulty, it is more likely that decreases in alpha-2 power were a result of somatosensory information processing.

PERSPECTIVES

In summary, the present study revealed decreased balance performance (i.e., postural sway) as well as frequency characteristics of cortical activity on basis of ICA-based source space analyses evoked by a continuous increase in balance task difficulty in healthy adolescents. Consistent with previous adult studies, we found increased theta frequency band power in frontal and central clusters reflecting attentional and error-based processes as well as decreased alpha-2 frequency band power, mainly in parietal areas, reflecting sensory information processing as a function of increasing postural demands and task difficulty. These findings support the notion that frontal, bilateral central as well as parietal areas are involved in postural control processes with increasing postural demands which may reflect the activity of cortical balance network. Further, we demonstrated that EEG source localization can be applied during a continuous balance task with increasing level of difficulty. Moreover, we were able to show that postural control strategies involve the activity of frontal, bilateral central as well as parietal brain areas and that activity of these areas change with increasing postural demands. Therefore, future studies may use high-density EEG systems to specify these functional areas and their time-frequency characteristics during increasing instability as well as cortico-muscular coherence analysis to link cortical to muscle activation patterns during increasing postural demands.

Author contributions

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

Conflict of interest

The authors declare that they have no conflicts of interest, financial or otherwise.

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