The Influence of Age and Sex on Balance Performance and Balance Trainability in Youth

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Abstract (English)

Background and aims: In youth, the postural control system is still developing due to various maturational processes. However, it is still not clear to what extent age (i.e., children vs. adolescents) and sex (i.e., girls vs. boys) affect balance performance in youth. Additionally, it may be speculated that age and sex may also affect the effectiveness of balance training in youth. Thus, the aims of this doctoral dissertation were to scrutinize the role of age and sex on balance performance and balance trainability in youth.

Methods: Within the framework of a systematic review and meta-analysis, one cross-sectional study, and two intervention studies the influence of age and sex on balance performance and balance trainability of children and adolescents were investigated. Types of balance performance (i.e., static, dynamic, proactive, reactive) were assessed by applying widely-used, standardized balance tests (i.e., one-legged stance on a force platform, 10-m walk test, Y-balance test, Push-and-release test) and corresponding equipment. Interventions included a standardized, five-weeks long balance training conducted during regular physical education lessons and the acquisition of a new dynamic balance task (i.e., balancing on a stabilometer) on two consecutive days before learning was assessed on the third day.

Results: Overall, the results indicated that adolescents show superior static, dynamic, and proactive balance performance compared to children. Additionally, associations between types of balance (e.g., static and dynamic) were small regardless of age and there were hardly significant differences between the investigated age groups. Contrary, balance training was in parts more effective in children than in adolescents, although both age groups benefited from respective training regimes. Concerning potential sex differences, results were inconclusive as depending on the type of balance better performances were observed in girls (i.e., static) as well as in boys (i.e., proactive). Further, similar performances of boys and girls were also found (i.e., dynamic). However, after practicing a new dynamic balance task learning effects were larger in girls than in same-aged boys.

Conclusions: The development of postural control does not seem to be complete at the end of childhood but to continue at least into adolescence. Consequently, balance exercises should be adapted to the age and thus performance level with balance training seeming to be especially effective in children. Additionally, regardless of age and development types of balance (e.g., static, dynamic) should be trained and tested individually/complementary. Further, sex-related performance differences should also be considered when balance

performance is judged or training regimes are developed. More specifically, during easier tasks (i.e., static) girls have an advantage and may therefore be provided with more difficult exercises, whereas boys show superior performances under more challenging conditions, which for instance also require sufficient muscular strength (i.e., proactive). Lastly, when practicing a new dynamic balance task boys may be given more practicing time in order to achieve similar learning effects as girls.

Abstract (German)

Hintergrund und Ziele: In der Jugend entwickeln sich die am Gleichgewicht beteiligten Systeme in Abhängigkeit vielfältiger Reifungsprozesse. Allerdings bleibt unklar inwieweit das Alter (z. B. Kinder vs. Jugendliche) und das Geschlecht (z. B. Mädchen vs. Jungen) Gleichgewichtsleistungen beeinflussen. Darüber hinaus könnte man annehmen, dass Alter und Geschlecht auch Auswirkungen auf die Effektivität von Gleichgewichtstraining haben. Das Ziel der vorliegenden Dissertationsschrift war daher, die Rolle von Alter und Geschlecht in Bezug auf Gleichgewichtsleistungen und die Trainierbarkeit des Gleichgewichts von Kindern und Jugendlichen eingehend zu untersuchen.

Methoden: Im Rahmen eines systematischen Reviews mit Meta-Analyse, einer Querschnittsstudie und zwei Interventionsstudien wurde der Einfluss von Alter und Geschlecht auf Gleichgewichtsleistungen sowie die Trainierbarkeit des Gleichgewichts von Kindern und Jugendlichen untersucht. Gleichgewichtsleistungen (statisch, dynamisch, proaktiv, reaktiv) wurden mit Hilfe weitverbreiteter, standardisierter Tests (z. B. Einbeinstand auf einer Kraftmessplatte, 10-m Gehtest, Y-Balance Test, Push-and-release Test) und entsprechendem Equipment erfasst. Die durchgeführten Interventionen umfassten ein fünfwöchiges, standardisiertes Gleichgewichtstraining, das im Rahmen des Schulsports durchgeführt wurde sowie die Aneignung einer neuen, dynamischen Gleichgewichtsaufgabe (Balancieren auf einem Stabilometer) an zwei aufeinanderfolgenden Tagen bevor am dritten Tag der Lernerfolg überprüft wurde.

Ergebnisse: Insgesamt zeigten Jugendliche signifikant bessere statische, dynamische und proaktive Gleichgewichtsleistungen als Kinder. Darüber hinaus zeigte sich, dass Assoziationen zwischen Gleichgewichtsformen (z. B. statisch und dynamisch) unabhängig vom Alter gering sind und zwischen den untersuchten Altersgruppen kaum signifikante Unterschiede bestehen. Umgekehrt führte Gleichgewichtstraining bei Kindern in Teilen zu größeren Anpassungen als bei Jugendlichen, wenngleich beide Altersgruppen vom Training profitierten. Bezüglich möglicher Geschlechtsunterschiede waren die Ergebnisse uneinheitlich, da in Abhängigkeit der Gleichgewichtsform sowohl bessere Leistungen von Mädchen (statisch) als auch von Jungen (proaktiv) sowie ähnliche Leistungen beider Geschlechter (dynamisch) beobachtet wurden. Nach dem Üben einer neuen dynamischen Gleichgewichtsaufgabe zeigten wiederum Mädchen größere Lerneffekte gegenüber gleichaltrigen Jungen.

Schlussfolgerungen: Die Entwicklung des Gleichgewichts scheint nicht in der Kindheit abgeschlossen zu sein, sondern mindestens bis ins Jugendalter fortzuschreiten. Dementsprechend sollten Gleichgewichtsübungen dem Alters- und damit dem Leistungsniveau angepasst werden, wobei ein Gleichgewichtstraining bei Kindern besonders effektiv zu sein scheint. Unabhängig vom Alter sollten verschiedene Formen des Gleichgewichts (z. B. statisch, dynamisch) einzeln und/oder komplementär getestet und trainiert werden. Leistungsunterschiede in Abhängigkeit von Geschlecht und Gleichgewichtsform sollten ebenfalls in die Bewertung von Gleichgewichtsleistungen und die Gestaltung von Gleichgewichtstrainings mit einbezogen werden. So sind unter einfachen Bedingungen (z. B. statisch) Mädchen im Vorteil und können somit schwierigere Übungen ausführen, wohingegen unter schwierigeren Bedingungen, die beispielsweise auch ein gewisses Maß an Kraft erfordern (z. B. proaktiv), Jungen besser Leistungen zeigen. Um beim Erlernen einer neuen dynamischen Gleichgewichtaufgabe ähnliche Lernerfolge wie Mädchen zu erzielen, sollte Jungen allerdings mehr Übungszeit gegeben werden.

1 General Introduction

This chapter will briefly outline the research problem which will be addressed in this doctoral dissertation. Further, the objectives of this thesis will be presented and an overview of the experimental studies conducted for and implemented in this work will be given.

1.1 Identification of the research problem

Numerous activities of daily life – from rather simple tasks such as walking or standing on one leg to more difficult tasks such as avoiding a fall following a stumble – require sufficient postural control. Walking for example is basically nothing else than a sequence of alternated one-legged stances with short periods of double-support in between during which the body has to be stabilised. However, as soon as one watches a toddler learning to walk one will realise that balance is not an innate ability, but has to be acquired during youth. Children struggle heavily when they learn to walk and will definitely fall multiple times until they have mastered this task. Luckily, in most of the cases the result of these falls is only a smudge on the trousers. Yet, even when children are able to walk properly their postural control is not fully developed. Indeed, balance and age show a curvilinear relationship with poor performance evident especially at young and old ages [1, 2]. For example, compared to young adults children and adolescents show greater postural sway during static standing [2], less mature gait patterns (e.g., time in double-/single-support) [3], and immature reactions to anticipated [4] as well as to unanticipated [5] perturbations.

Deficits in balance performance in children and adolescents have been attributed to the ongoing maturation particularly of the central nervous system [6, 7]. Besides these developmental limitations of balance performance, secular trends have been reported indicating that balance performance in youth has decreased over the past decades [8] which may be attributed to lifestyle changes (e.g., digitalisation, urbanisation) as children and adolescents spend a considerable amount of their daily time sedentary [9, 10]. Both, physical immaturity [11] as well as poor motor performance [12, 13] represent major intrinsic (person-related) risk-factors for sustaining falls and injuries in children and adolescents. In fact, in youth falls account for up to 50% of all injuries treated in hospitals [14] and the majority of these falls (i.e., 75%) occur on plain ground [14] and rarely involve contacts or collisions [15]. Further, an association between poor balance performance and an increased injury risk has been proven for various sports (e.g., basketball, soccer) in children and adolescents [16-18]. For example, McGuine and colleagues [16] observed seven times as many ankle sprains in sixteen-year-old basketball players who showed poor balance performance (i.e., high sway values during one-legged stance with eyes open and closed) compared to those exhibiting good postural control (i.e., low sway values during one-legged stance with eyes open and closed). Besides adverse physiological and psychological effects, fall-related injuries do also cause a substantial economic burden. In the United States of America for instance it is assumed that the costs of fall-related injuries in children and adolescents amount to more than 20 million dollars per year [19].

In contrast to the negative outcomes associated with poor balance performance in youth, sufficient balance is considered to be beneficial in children and adolescents. For example, postural control is positively associated with regular physical activity [20, 21]. More specifically, it has been shown that physically active ten-year-old children exhibit less postural sway during different stance variations and when walking than their less active peers [20]. Further, there seems to be an association between balance ability and athletic performance. In a review article investigating this relationship, Hrysomallis [22] revealed that balance performance differed according to the sports conducted (e.g., gymnasts show superior performance compared to swimmers) as well as in relation to the competition level (e.g., superior performance of national-level compared to regional-level soccer players). Moreover, in sports such as rifle shooting or archery good postural control was associated with better sport specific performance [22].

The aforementioned studies highlight the great importance of sufficient balance in children and adolescents. Yet, in order to develop specific training programs, knowledge about the development of balance in youth is indispensable. However, in this regard studies have reported conflicting results with some indicating that balance is adult-like already at the end of the first decade of life [23-25], whereas others report continuing performance increases up to late adolescence [26, 27]. Additionally, it has been suggested that rather than being a "general ability" balance seems to be task-specific [21] indicating that a person may exhibit good performance during static tasks (e.g., one-legged stance) but show deficits when performing a dynamic task (e.g., responding to perturbations) or vice versa. If balance performance is affected by age in youth, it may consequently be hypothesised that such age-related differences might also affect associations between types of balance (e.g., static and dynamic). However, instead of using identical testing procedures in children and adolescents, studies have so far either focused on children [28] or adolescents [29] but not on both and used different methodological approaches (i.e., biomechanical vs. physical fitness tests; force plates vs. motion capture systems; firm vs. foam ground; eyes opened vs. closed, etc.) [30].

Further, when considering that balance performance in youth is largely regulated by maturation, it may be speculated that in youth it is not only affected by age but also by sex. For instance, based on observations one could argue that girls tend to participate in sports involving a lot of balance (e.g., dancing, gymnastics) more frequently than boys which may result in better balance performance of girls compared to boys. Additionally, girls are known to mature earlier than boys [31, 32]. Consequently, girls might exhibit better balance performance than same-aged boys. However, studies investigating sex-related differences in balance performance in youth have found mixed results with some reporting better performances of girls compared to boys [26, 33, 34], some studies [35, 36] not finding differences between girls and boys at all or even observing better performances in boys at least in some measures as compared to girls [37].

Deeper knowledge on the development of balance in youth and particularly on how it is affected by age and sex is of major importance when designing programs that aim to improve balance performance in youth. More specifically, if balance performance is affected by age and sex, youth training programs can take into account these differences by providing individuals who show advanced performances (e.g., adolescents, girls) with different and/or more difficult exercises. With respect to age, there are only a few balance training studies [38, 39] available which have some methodological flaws. For instance, the authors [38, 39] did not adjust their analysis for baseline differences between intervention and control groups. Concerning the influence of sex on balance training in youth, evidence is even scarcer. In fact, to the best of the author's knowledge no study has addressed this issue in detail so far.

To summarise, this chapter has briefly outlined the important role of balance in youth and it has been highlighted that although age and sex seem to affect balance performance in youth in some way the actual extent of this influence remains unclear. Yet, knowledge about the influence of age and sex on balance performance and balance training effectiveness in youth is of major importance for practitioners such as clinicians, teachers, and sports coaches to for instance develop effective training programs. High quality studies assessing all types of balance performance using standardised tests in clearly defined age groups can provide a better understanding of the influence of age and sex on balance performance and balance training in school-aged youth. Therefore, the aim of this doctoral dissertation is to provide deeper insights into the influence of age and sex on balance performance and balance training in youth.

1.2 Objectives of this doctoral dissertation

The aim of this work is the empirical verification of the voids in the literature highlighted before. As illustrated by the rather conflicting results concerning the influence of age and sex on balance performance in youth and limited to non-existent findings on age- and sex-related effects on balance training in youth there is a definite need to scrutinise the role of age and sex on balance performance and balance training in youth. Thus, the objectives of this thesis were to investigate the role of age and/or sex of school-aged youth (I) on balance performance, (II) on relationships between types of balance, (III) on the trainability of balance, and (IV) on learning of a new balance task. For this purpose, a systematic review and meta-analysis [40], one cross-sectional study [41], and two intervention studies [42, 43] were conducted. Details on the respective studies are presented below:

<u>Systematic Review and Meta-Analysis</u>

I **Schedler S.,** R. Kiss and T. Muehlbauer, *Age and sex differences in human balance performance from 6-18 years of age: A systematic review and meta-analysis.* PLoS One, 2019. **14**(4): p. e0214434. [40]

<u>Cross-Sectional Study</u>

II **Schedler S.**, E. Abeck and T. Muehlbauer, *Relationships between types of balance performance in healthy individuals: role of age.* Gait Posture, 2021. **84**: p. 352-56. [41]

<u>Intervention Studies</u>

III **Schedler S.** et al., *Effects of Balance Training on Balance Performance in Youth: Are There Age Differences?* Res Q Exerc Sport, 2020. **91**(3): p. 405-414. [42]

IV **Schedler S.**, et al., *Effect of practice on learning to maintain balance under dynamic conditions in children: are there sex differences?* BMC Sports Sci Med Rehabil. 2020. **12**: p. 15. [43]

The results of these studies will provide substantial contributions to the knowledge on the influence of age and sex on balance performance in youth. This knowledge will help to understand the development of balance in youth and aid practitioners such as clinicians, teachers, or sports coaches when assessing balance performance or implementing training programs for instance to reduce injury risk in school-aged youth.

2 Theoretical Background

First, the following chapter will provide basic definitions. Thereafter, a brief literature review of current knowledge on the influence of age on balance performance, associations between types of balance and balance training will be given. Lastly, the role of sex will be discussed with regard to balance performance and balance trainability in youth. Based on these information, the underlying research questions and hypotheses of this doctoral dissertation will be deduced and stated.

2.1 Defining balance

From a biomechanical perspective an object is in balance when the sum of the resultant net force of all forces acting on it equals zero [44]. In static situations, this state is highly dependent on the position of the centre of mass relative to the base of support. More precisely, as long as the line of gravity falls within the base of support an object is in balance, whereas this state is endangered as soon as the line of gravity falls beyond the base of support. In humans for example, during static bipedal standing the line of gravity lies between the base of support (i.e., the feet). However, contrary to objects humans can actively activate their muscles in order to move and interact with their environment. Thus, in humans balance has not only to be maintained in static but also in dynamic situations. For example, during walking or running the centre of mass is constantly moving while the base of support changes sequentially. In addition, balance is not only challenged by simple movements but especially in response to perturbations. Perturbations can be either self-inflicted, for instance when reaching for a bottle on the opposite end of a table where the centre of mass is actively moved to the boundaries of the base of support or external, for example due to an unexpected slip on a wet floor where the centre of mass is passively put beyond the base of support.

The aforementioned situations are rather different in nature and pose various challenges to the postural control system. Therefore, Shumway-Cook and Woollacott [45] have introduced a model in which sufficient balance is a prerequisite to perform movements in general and simple motor tasks in particular (e.g., standing, walking, climbing stairs) which result from interactions between the individual, the environment, and the task (Fig. 1).

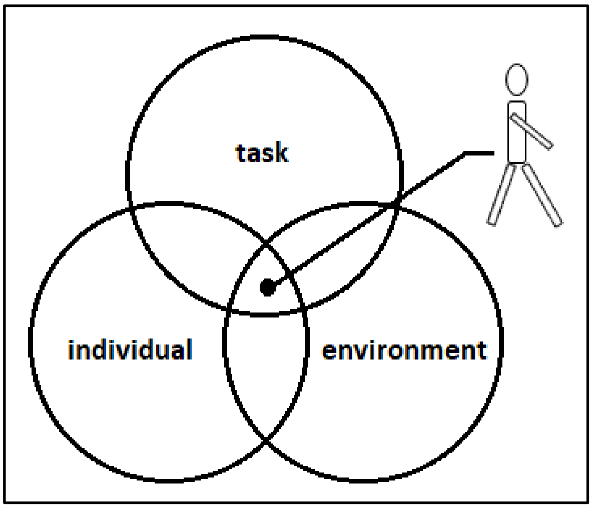

Figure 1. Interaction between task, individual, and environment according to Shumway Cook & Woollacott [46].

With respect to the individual, a person can for example resort to certain motor (e.g., neuromuscular system), sensory (e.g., perceive and process proprioceptive input), and cognitive (e.g., attention, problem solving) skills to maintain balance in different situations. Further, all movements including simple motor tasks have to be performed in different environments (e.g., walking on plain vs. uneven ground) which may challenge the postural control system. Lastly, and as indicated before most important with respect to the present thesis, Shumway-Cook and Woollacott [46] differentiate between certain types of balance according to the different tasks these pose to the postural control system. More specifically, they distinguish between static steady-state, dynamic steady-state, proactive, and reactive balance (Fig. 2).

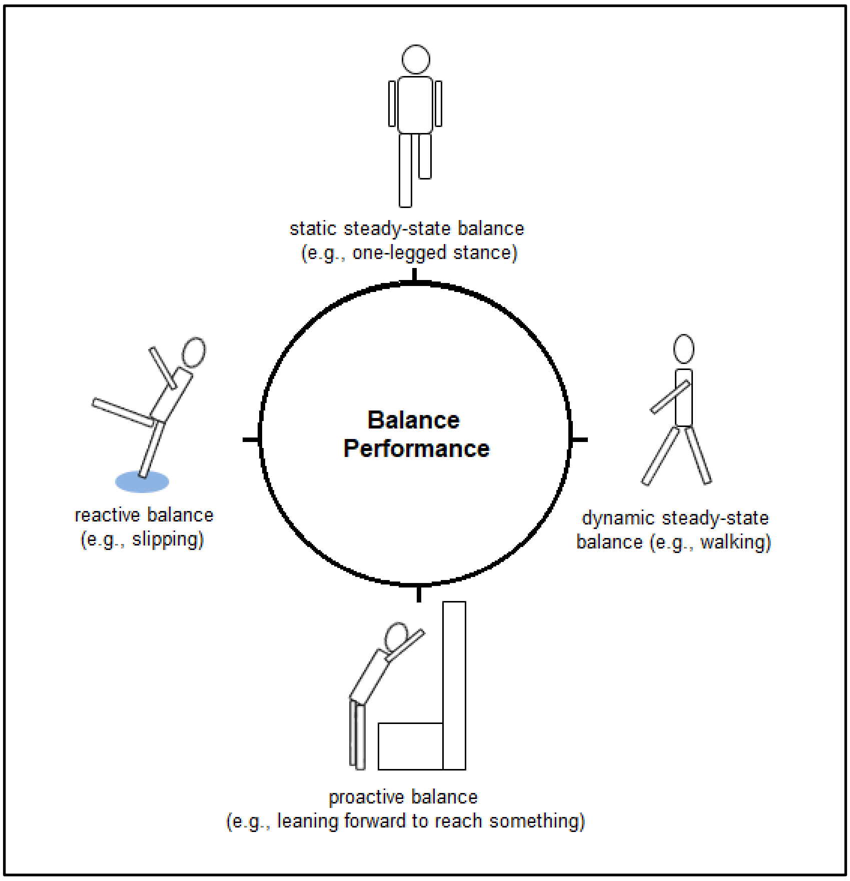

Figure 2. Types of balance performance as postulated by Shumway Cook & Woollacott [46].

These types of balance will be described in detail in the following paragraphs.

2.1.1 Static steady-state balance

Static steady-state balance is required in static situations such as sitting or standing. In static situations the line of gravity falls within the stationary base of support. Although, maintaining static balance seems to be rather simple at first, the difficulty of this task can be increased by simple changes to the base of the support. For example, reducing the base of support during two-legged standing by moving the feet closer together from a hip- or shoulder-width stance to a stance where the inner sides of the feet touch each other results in decreased stability. Further limiting the base of support by for instance putting one foot in front of the other so that the heel of the front foot touches the toe of the back foot (i.e., tandem stance) or by standing on one leg rather than on two poses even larger challenges to the postural control system and usually results in increased swaying [47]. Differences in static balance performance are usually assessed in more difficult situations like the one-legged stance in healthy populations as the easier to perform stance variations (e.g., two-legged stance) are not sensitive enough to detect differences between individuals. Contrary, in clinical populations (e.g., patients with Alzheimer’s disease) rather simple stance variations like the tandem stance may be sufficient to discriminate between individuals with good and poor static balance. To assess balance performance during static standing, simple measures such as the time in balance (i.e., before touching the floor with the non-supporting leg during one-legged stance or taking a step during two-legged stance variations) can be used. More sophisticated assessments usually include force plate measurements quantifying the movement of the centre of pressure (CoP) which is associated with body sway. Although, measures of static balance are usually included in studies on balance performance, it might be considered as being less relevant from a practical point of view since humans by nature interact with their environment through movements.

2.1.2 Dynamic steady-state balance

During dynamic activities such as walking or running both the centre of mass as well as the base of support are moving quite steadily. For example, when walking forwards the base of support moves constantly forward and changes sequentially from a two-legged stance to a one-legged stance which is followed by another phase of double support. Simultaneously, the centre of mass moves forward from its approximate location during static, two-legged standing (i.e., in the centre of the body near the belly button) as well as to the side of the respective stepping leg. Thus, balance has to be maintained throughout constantly but rather steadily changing conditions. However, the centre of mass predominantly remains within the base of support. Tests of dynamic steady-state balance often require individuals to walk a certain distance (e.g., 5 m, 10 m) at self-selected pace. Simple and easy to assess variables include walking speed which is considered to be a surrogate marker of dynamic balance performance and step frequency (e.g., cadence). Further insights can be provided by gait analysis using kinetic (e.g., via force plates), kinematic (e.g., video-analysis) and/or electromyographic data which can be used to analyse variables such as ground reaction forces, stride length, time in single-support, or muscle activity. As human activities usually include movements, dynamic balance is of high relevance to successfully perform a multitude of activities of daily life.

2.1.3 Proactive balance

There are numerous situations where a person actively moves his/her centre of mass close to or even beyond the boundaries of the base of support, thus destabilising the body and increasing the risk of falling. Therefore, proactive balance requires a person to predict the extent of a postural disturbance caused by a voluntary upcoming movement and adequately activate muscles to counteract the resulting destabilising forces in order to maintain balance. Examples are a person who is reaching for the water with one foot to check the water temperature while standing on the edge of a swimming pool or someone who is leaning forward in order to reach a bag in the overhead locker while standing on tiptoe. In sports, soccer players for instance require proactive balance when they shield the ball in a one on one situation and expect to be pushed by an opponent. Therefore, proactive balance especially requires feedforward movement control [48, 49]. Tests to measure a person's proactive balance performance often consist of reaching tasks with either the upper (e.g., Functional reach test) or lower extremities (e.g., Y-balance test). These tests usually quantify the maximal reach distance a person is able to obtain without falling relative to extremity length.

2.1.4 Reactive balance

A major threat to a person's balance are unexpected perturbations where either the centre of mass is suddenly pushed beyond the boundaries of the base of support or the base of support is rapidly moved so that the line of gravity falls outside of the base of support. The former for example happens when a person is standing in a moving bus which brakes unexpectedly, whereas an example for the latter is a slip on a wet floor. In most sports sufficient reactive balance is of major importance, for instance during a tackling in team sports. These examples also highlight the great importance of sufficient reactive balance to avoid falling and illustrate that appropriate feedback [48, 49] is essential to stabilise the body in situations where reactive balance is challenged. Due to the involvement of unexpected perturbations assessing reactive balance performance is comparatively complex and generally requires sophisticated instruments. In this regard, free swinging platforms and specially designed treadmills which enable researchers to induce unexpected perturbations have been used often in combination with electromyography to analyse muscular responses to perturbations. Only the so called Push-and-release test which involves a person to lean backwards against the hands of an examiner who then suddenly removes the hands which then requires the person to step in order to avoid falling can be performed without the use of special equipment.

2.2 Associations between types of balance in youth

As stated in chapter 2.1, balance can be subdivided into different types (e.g., static, dynamic, etc.). It has previously been questioned whether these types of balance performance are associated with each other. For example, let us imagine we measured a person's static steady-state balance performance and determined it to be "good" whatsoever "good" means exactly. Does this information give us any clues about this person's dynamic, proactive, or reactive balance performance? If it did, this would have major practical implications (e.g., for physical education [P.E.] teachers or coaches) as it would for instance suffice to only measure performance in one type of balance (e.g., static balance) to draw conclusions on a person's capability in other types of balance (e.g., dynamic, proactive, and/or reactive balance). Similarly, it would also imply that training one type of balance (e.g., proactive balance) would probably also improve performance in another type of balance (e.g., reactive balance). Therefore, several studies have addressed this issue by assessing performances in two or more types of balance and calculating correlation coefficients for associations between types of balance performance.

For example, Muehlbauer et al. [28] analysed associations between static steady-state (i.e., two-legged stance), dynamic steady-state (i.e., 10-m walk test), proactive (i.e., Functional reach test), and reactive balance (i.e., perturbed stance) in healthy children aged seven to ten years. Except for two comparisons (i.e., anterior-posterior sway during static and perturbed stance: $r = .458$, $p < .05$; medio-lateral sway during static stance and performance in the Functional reach test: $r = -.530$, $p < .05$) they observed only small-sized ($-.232 \leq r \leq .431$) and non-significant ($p > .05$) correlations between types of balance performance. Similarly, Granacher and Gollhofer [29] investigated the relationship between static (i.e., one-legged stance) and reactive (i.e., perturbed one-legged stance) balance in adolescents aged 16-17 years and only found small-sized ($-.189 \leq r \leq .027$) and non-significant ($p > .05$) correlations. Other studies reported similar results in children [50-52] and adolescents [53, 54] as well as in groups of young [55], middle-aged [56] and old adults [57]. Therefore, it has been concluded that balance is task-specific implying that a person's performance in one type of balance does not provide information on this person's performance in another type of balance.

Although the concept of task-specificity of balance has been widely accepted, it may be argued that as balance performance changes with age in youth associations between types of balance might also differ according to age. For example, based on the assumption that balance performance is still developing in children they might be able to effectively switch between the execution of different balance tasks as they possess a comparatively low level of task automation. Contrary, young adults possess a high level of task automation which increases the specificity of movement control and thus curtails their ability to switch between the execution of various balance tasks. Consequently, it may be speculated that relationships between types of balance might be larger in children as compared to adolescents and/or young adults. In this regard, Kiss et al. [30] analysed and statistically compared associations between types of balance between various age groups (i.e., children, adolescents, young adults, middle-aged adults, old adults) in a systematic review and meta-analysis. Confirming the results of single studies, associations between types of balance were overall small and non-significant. When statistically comparing correlations of different types of balance between age groups, these researchers [30] however revealed that the association between static and dynamic steady-state balance was significantly smaller ($p < .01$) in children ($r = .09$) compared to old adults ($r = .31$). Although this finding is in contrast to the considerations we have just made, Kiss et al. [30] pointed out that this age-effect might result from different methodological approaches as various balance tests and measures were used in the included studies and most of the studies only investigated a single age group which questions the validity of the results. To give an example, both Humphriss et al. [51] as well as Witkowski et al. [53] analysed associations between static and dynamic balance. However, while Humphriss et al. [51] investigated associations between heel-to-toe stance on a beam (static balance) and heel-to-toe walking on a beam (dynamic balance) in ten year-old children, Witkowski et al. [53] examined the relationship between performances in the flamingo (static balance) and marching (dynamic balance) test in adolescents aged 14 to 15 years. Obviously, a direct comparison of these results is difficult.

Although, the aforementioned studies provide some insights into the influence of age on associations between types of balance in youth, there are also several methodological inconsistencies and/or limitations associated with them. Especially in youth, studies have been limited to certain types of balance (e.g., static and dynamic) and single age groups (e.g., children or adolescents). Moreover, the use of different balance tests and measures between studies further limits their comparability. This highlights the need for high-quality studies assessing balance performance in various age groups using identical methods (i.e., test conditions, test equipment, measures) and statistically comparing associations between types of balance according to age.

2.3 The influence of age on balance performance in youth

The vast majority of studies on the development of balance performance in youth has shown performance increases with advancing age in youth. Already in the early 1960s, Sheldon [58] used a custom-built frame placed on participants' shoulders that was connected to a springloaded pencil to quantify participants' body movements during standing on graph paper. The resultant graphs clearly illustrated that postural sway decreased from 6-9-year-olds, over 10-14-year-olds, to 16-19-year-olds. Similar results were reported by Riach and Hayes [59] who examined postural sway during two-legged stance in children aged two to fourteen years using more sophisticated instruments like a force platform. They observed decreasing sway in both anterior-posterior as well as medio-lateral direction with increasing age indicating larger stability and better performance of older compared to younger individuals. Besides these findings concerning balance performance in youth under static conditions, studies focusing on balance performance under dynamic conditions have reported similar findings. For instance, regarding dynamic steady-state balance gait velocity has been shown to increase with age in youth [24, 25]. More specifically, Norlin et al. [60] revealed a statistically significant ($p < .01$) correlation ($r = .97$) between self-chosen gait velocity during very slow, ordinary, and very fast walking and age in individuals aged three to sixteen years. Similarly, Chester et al. [61] showed gradually increasing gait velocities when comparing groups of children aged three to four, five to six, seven to eight, and nine to thirteen years. Moreover regarding proactive balance performance, Hay and Rendon [62] for instance reported that postural sway in anterior-posterior direction in response to arm raising decreased with age in groups of children aged 3-5, 6-8, and 9-10 years and was lowest in young adults. Lastly, with respect to reactive balance performance Waelchli and colleagues [39] observed less sway in twelve- compared to six-year-olds following perturbations from an unknown direction. Thus, there is generally consensus that balance performance increases in youth.

Due to the physical changes (e.g., body growth) occurring in youth it seems reasonable to assume that these developments also account for the improvements in balance performance. However, contrary to this assumption studies [59-61] have found that anthropometric changes cannot fully explain increasing balance performance in youth. Using stepwise linear regression Riach and Hayes [59] for example showed that body height, body mass, and even age could only explain a small portion of the variability of postural sway in youth aged 6-19 years. Therefore, increasing balance performance in youth has been linked to improved sensory integration [26, 27, 63], the ability to task-specifically use different postural control strategies [64, 65] as well as to advanced brain maturation [66]. All of the aforementioned factors are largely affected by the development of the central nervous system and according to Kraemer and Fleck [67] the maturation of the central nervous system continues into adolescence, although major developments occur during childhood. Thus, one could expect that balance performance also continues to increase throughout adolescence.

Contradictory to this assumption, studies on age-related differences in balance performance in youth reported inconsistent results. Shumway-Cook and Woollacott [23] analysed postural sway as well as muscular activity during two-legged stance under different sensory conditions (e.g., surface static/moving, eyes open/closed) in children aged 15 months to ten years and compared the results to performances of adults. Although performances changed with increasing age, children aged seven to ten years performed similarly to adults leading the authors to conclude that postural control is adult-like in this age group. In contrast, when Rival and colleagues [68] compared postural sway during two-legged stance with eyes closed between children (6-10 years) and adults, they found performance to increase with age but it did not reach the adult-level in the ten-year-olds, indicating that balance performance improves beyond the end of the first decade of life. Moreover, in a study by Hsu and colleagues [69] sway velocity during two-legged stance under different conditions (i.e., firm/foam ground, eyes open/closed) reduced with increasing age in children aged three to twelve years old, yet only performances of the twelve-year-olds were comparable to those of adults. Lastly, using the sensory organization test Steindl et al. [26] and Hirabayahi and Iwasaki [27] revealed that some aspects of postural control, especially vestibular function do not even reach the adult-level before the age of 15.

To summarise, although studies indicate that balance performance in youth increases with age there is no consensus as to how long this process continues. One explanation for the inconsistency of results may be that previous studies did not clearly discriminate between children and adolescents. For instance, Sheldon [58] grouped individuals aged 10-14 years which include children and adolescents at various stages of development. Similarly, most studies investigated only a certain type of balance (e.g., static) and it may be hypothesised that types of balance do not develop simultaneously. Consequently, there is a need to investigate the influence of age on balance performance in youth in more detail by using clearly defined age groups and identical measures covering all aspects of balance performance (i.e., static/dynamic steady-state, proactive, reactive).

2.4 The influence of sex on balance performance in youth

In the preceding paragraph, it was highlighted that improved balance performance in youth seems to be the result of advanced maturation. However, girls and boys do not develop at the same rates in youth. More precisely, from a developmental perspective girls have an advantage over boys as they mature earlier [32, 70, 71]. For instance, girls enter adolescence on average two years earlier than boys which includes the earlier onset of adolescent growth and major changes in hormonal status [72]. Moreover, girls engage in sports such as ballet or gymnastics more frequently than boys [73] and these sports are known to foster balance performance [74]. Thus, it seems reasonable to assume that in youth balance performance also differs according to sex with girls exhibiting better performances than same-aged boys.

Indeed, studies investigating the effect of sex on balance performance in youth reported mixed results. Several studies [26, 33, 34, 59, 75, 76] observed better performances of girls compared to boys. For example, Riach and Hayes [59] found that boys swayed considerably more than same-aged girls until the age of twelve when standing on both feet with eyes open and closed, respectively. Similarly to the explanations for increasing balance performance with age in youth, better performance of girls compared to boys has been attributed to improved sensory integration [26], advanced neuromuscular development [33], and the use of more adult-like postural control strategies [75]. Other explanations related to behavioural differences between girls and boys with girls being less hyperactive [27] and more attentive [26] during balance tests which usually also require high concentration. On the contrary, there are also studies [35, 36] which did not find differences in balance performances between girls and boys. Butz and colleagues [35] for example observed comparable performances of girls and boys aged five to twelve years old who performed the pediatric balance scale. Finally, Holden and colleagues [37] longitudinally analysed Y-balance test-performance in adolescents and observed better performances of boys compared to girls in two (i.e., posteromedial reach and posterolateral reach) out of three reach directions.

The inconsistent findings regarding the influence of sex on balance performance in youth may again be explained by methodological differences between studies such as grouping girls and boys according to chronological rather than biological age, the investigation of different types of balance performance and the use of different balance tests and measures. Consequently, there is a need to investigate the influence of sex on balance performance in youth in more detail by either grouping individuals according to biological age or focusing on children who have not yet entered adolescence to minimise the influence of maturational differences between girls and boys.

2.5 Balance practice and training in youth

As previously described poor balance performance is considered to be a major intrinsic risk factor for sustaining falls and/or injuries in youth whereas good postural control is associated with higher levels of physical activity and increased sports performance. Consequently, it is not surprising that research has also aimed to improve balance performance in children and adolescents by means of balance training. More importantly, balance training might be especially useful in children and adolescents for at least two reasons. First, in order to increase children's and adolescents' balance performance and thus on the one hand improve their overall motor performance and on the other hand to reduce their risk of sustaining falls or injuries. Second, as the central nervous system as well as the postural control system are still developing in children and adolescents balance training may be particularly effective in these age groups.

The effects of specific training interventions can be assessed either in the laboratory or the field. Laboratory-based experiments have the advantage that test conditions can be controlled by the experimenter and thus possess high internal validity. Using these laboratory conditions, studies on motor training typically investigate the acquisition of one new motor task (e.g., balancing on a wobbleboard). However, life is taking place outside of laboratories and therefore the effects of specific interventions should not only be proven in the laboratory but also in the field. Although such studies usually have poorer internal validity due to the experimenter's limited influence on factors surrounding the test, they possess high external validity due to the more realistic setting.

Laboratory-based studies on motor learning as for instance the acquisition of an unfamiliar balance task mostly start with an acquisition phase during which participants are given a certain number of trials to practice the task, which usually includes the provision of feedback on participant's performance (e.g., providing knowledge of results). Practicing should lead to short-term adaptations illustrated by performance-increases with repeated trials. Following this phase of acquisition, retention and/or transfer tests are carried out to assess long-term adaptations indicating learning of the practiced task [77]. These tests require the execution of the practiced task under slightly different conditions (e.g., no feedback) and are usually carried out at least 24 hours after the last practice session so that short-term adaptations have dissipated [78]. Performance in the retention and/or transfer test should still be better than performance at the beginning of the acquisition phase to indicate learning. With respect to balance, studies on motor learning have used tasks such as balancing on a stabilometer [79, 80], on a wobbleboard [81], or on pedalos [82]. Generally, these studies confirmed the aforementioned assumptions and reported performance increases throughout practicing on the one hand and long-term adaptations which were illustrated by still improved performance in retention and transfer tests on the other hand. For example, in a study by Becker and Smith [82] the time to complete a seven meter course on a double pedalo decreased over 20 practicing trials and was still improved in a delayed retention test in children (8-10 years) as well as in young adults (19-26 years).

Besides this laboratory research on learning processes of a new motor or balance task in youth, several studies have investigated the effects of more complex balance training programs in the field. These studies have been conducted with groups of healthy children [83-86] as well as with adolescents [87-89]. The balance training regimes applied in these studies generally lasted several weeks (i.e., 4-12 weeks) with training sessions performed regularly (i.e., 2-7 sessions/week) which consisted of classic balance exercises such as performing two- or one-legged stances under different sensory conditions (e.g., eyes opened/closed, stable/unstable ground) and using various equipment like ankle-discs [86], wobble-boards [87] or slacklines [83]. Overall, most of these studies revealed balance training to be effective in order to improve balance performance in children and adolescents. For example, following six weeks of balance training using a slackline, standing time on the slackline significantly increased in ten year-old children, whereas no changes were observed in an active control group [83]. These results were confirmed by findings from a systematic review and meta-analysis [90]. To specify, by systematically analysing and quantifying effects of balance training in youth (6-19 years) reported in single studies Gebel et al. [90] found moderate to large effect sizes in favour of balance training for measures of static (*SMD* = 0.71) and dynamic (*SMD* = 1.03) balance.

Consequently, balance training can be considered to represent an effective means to improve balance performance in youth. However, with respect to the influence of maturation on balance performance in youth it may be hypothesised that the effectiveness of balance practice and balance training in youth differs according to age and/or sex. Such knowledge would be of major importance for practitioners such as P.E. teachers or sports coaches. For instance, if the effectiveness of balance practice and/or training differs by age and/or sex individuals who show advanced performances may be given tasks of higher difficulty and/or complexity in order to train most effectively. Therefore, it seems reasonable to take a closer look at current knowledge on the influence of age and sex on the effectiveness of balance training in youth.

2.5.1 Age-effects of balance training in youth

The marked developments (e.g., neuromuscular system, sensory systems) taking place during childhood and adolescence may, as has been described in chapters 2.3 and 2.4, not only have an impact on balance performance but also affect the trainability of balance in youth. On the one hand, one could for instance argue that adaptations to balance training in youth may depend on the level of performance. For example, a lower level of performance, as often observed in children, implies larger adaptive reserves which could facilitate particularly large effects of balance training. On the other hand, it may be possible that the balance control system has to attain a certain developmental stage (e.g., adolescence) so that training can be most effective or effective at all. In this case, being too young or immature would prevent optimal adaptations to balance training.

Supporting the latter notion, Granacher et al. [86] did not find statistically significant changes in balance performances of six-year-old children following four weeks of balance training conducted during regular P.E. lessons. The authors expressed that the immaturity of the postural control system in young children may be one explanation for the non-significant findings. Contrary, in their systematic review and meta-analysis Gebel et al. [90] aggregated results on static and dynamic balance to compare the effect sizes for the effectiveness of balance training between children and adolescents, which indicated larger effects of balance training in the younger ($SMD = 1.28$) compared to the older ($SMD = 0.84$) age group. However, this difference was not statistically significant ($p > .05$). Nevertheless, the authors [90] emphasised the preliminary character of their findings due to the small number of included studies (N = 17) and high heterogeneity between studies ($I^2 = 66\text{-}83\%$). For example, Emery et al. [66] investigated the effects of six weeks balance training (e.g., two- and one-legged stance exercises with eyes open/closed on a wobble board) on static (i.e., timed one-legged stance with eye closed on firm ground) and dynamic (i.e., timed one-legged stance with eye closed on foam ground) balance performance in adolescents (14-19 years old), whereas Dobrijevic et al. [91] analysed static (i.e., one-legged stance on a balance beam with the dominant leg and eyes open) balance performance in a group of young female gymnasts (6-7 years) following twelve weeks of balance training using two- and one-legged stances on various unstable devices (e.g., T-board, half-globe board, soft mattresses) with changing visual input (i.e., eyes open/closed) and additional tasks (e.g., balancing a ball). Thus, there seems to be a paucity of studies comparing the effects of a standardised balance training in different age groups using identical balance tests and measures.

To the best of the author's knowledge, to date there are only two studies [38, 39] which have addressed this issue by conducting the same balance training program in groups of children and adolescents of different ages. Following five weeks of a specifically designed child-oriented balance training in children and adolescents aged six to fifteen years, Waelchli and colleagues [38] observed improvements in dynamic balance performance (i.e., CoP sway during one-legged stance on a spinning top and on a free-swinging platform) that were largest in the youngest age group. It was concluded that balance training is particular effective in young individuals from the age of six years on. In contrast, when researchers from the same group analysed the effect of age on BT-related improvements on balance performance following anticipated (i.e., direction known) and non-anticipated (i.e., direction unknown) perturbations they did not find significant differences between six- and twelve-year-olds [39]. However, although the same balance training was applied in both studies one study [38] examined its effects on static and dynamic balance performance in groups of six-, eleven-, and fourteen-year-olds, whereas the other [39] analysed measures of proactive and reactive balance performance in six- and twelve-year-olds. Additionally, analyses in both studies [38, 39] were not adjusted for existing baseline differences in balance performances between intervention and control groups. Consequently, although these two studies provided insights into age-dependent adaptations to balance training in youth, they comprised methodological flaws and there is still no study available which compares the effects of a standardised balance training on all types of balance (i.e., static, dynamic, proactive, reactive) in children and adolescents using identical balance tests and measures.

This chapter has clearly outlined present knowledge on learning of a new balance task as well as on the effects of balance training programs in youth. Due to in parts conflicting evidence and a void of literature investigating the effects of age on motor learning processes and balance training, respectively, it has been pointed out that further studies are needed to scrutinize the influence of age on balance trainability in youth.

2.5.2 Sex-effects of balance training in youth

The presence of maturational differences between girls and boys has been proven in several studies (e.g., [32, 70, 71]) which generally revealed that girls mature on average two years earlier than boys. Given that balance in youth seems to be largely affected by maturation it seems therefore likely that adaptations to balance training may also differ between girls and boys. Surprisingly, this question has been hardly investigated so far. In fact, to the best of the author's knowledge the influence of sex on the effectiveness of balance training in youth has only been addressed in a systematic review and meta-analysis [90] which analysed dose-response relationships of balance training. Although, the observed effect sizes for the effectiveness of balance training in youth were larger for boys (*SMD* = 1.07) as compared to girls (*SMD* = 0.42), this difference was not statistically significant ($p > .05$). It was therefore concluded that sex did not seem to have a moderating effect concerning the effectiveness of balance training in youth [90]. Yet, due to limited data availability Gebel et al. [90] had to aggregate results from studies investigating different types of balance (e.g., static, dynamic) which used different tests (e.g., physical fitness vs. biomechanical) which limits the reliability of the reported findings.

Consequently, the presence of sex effects of balance training in youth remains questionable. If we assume that as stated earlier (see chapters 2.3 and 2.4) maturational processes in adolescence play a major role in the development of postural control it may be difficult to discriminate between actual sex-related differences and differences originating from developmental differences between individuals when investigating subjects who have already entered adolescence. Therefore, it may be reasonable to investigate potential differences between girls and boys in young children to eliminate the impact of the individual onset of puberty.

2.6 Research questions and hypotheses

The preceding chapters gave a brief overview over current knowledge on the influence of age and sex on balance performance and associations between types of balance in youth. It was further outlined that age and sex may also influence the effectiveness of balance training in youth. Based on the inconsistent findings it was additionally highlighted that the question how balance is affected by age and sex in youth needs further investigation. The primary aims of this doctoral dissertation were therefore to analyse how age and sex on the one hand affect balance performance in youth and on the other hand how the effectiveness of balance training might be influenced by age and sex in youth, respectively. Figure 3 illustrates the general scientific framework of this doctoral dissertation.

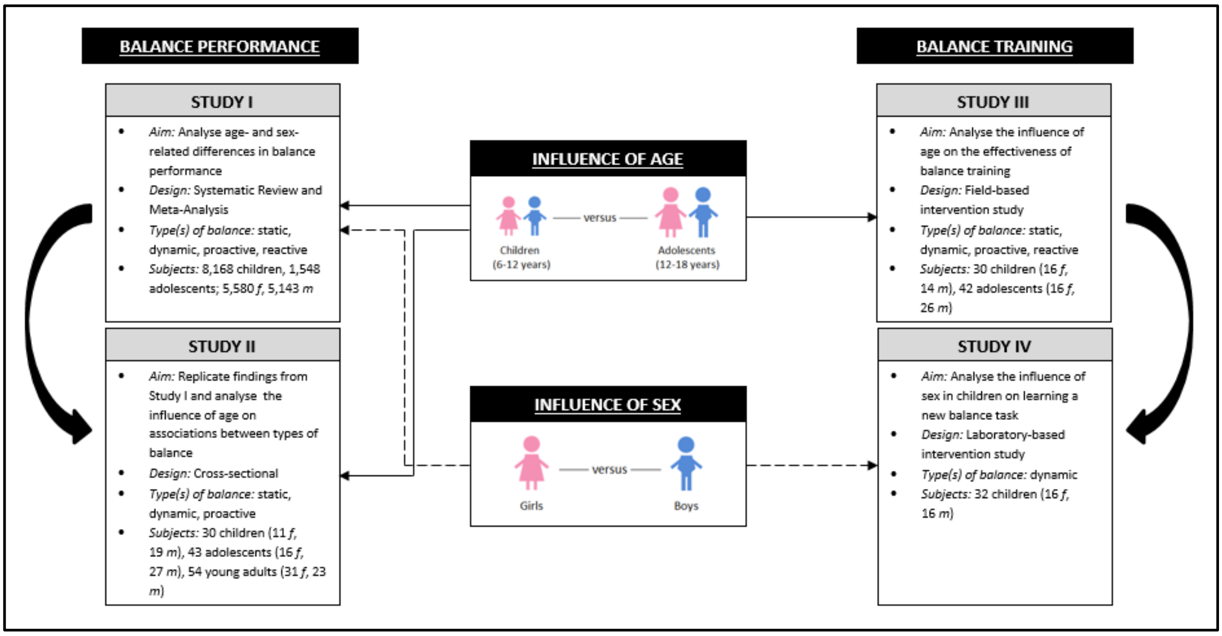

Figure 3. Illustration of the scientific framework of the presented doctoral dissertation. *f* female, *m* male

In the following paragraphs, the detailed research questions and respective hypotheses will be presented.

2.6.1 Research questions examining the role of age

With advancing maturation, physical as well as neural developments proceed. Thus, it seems reasonable to assume that balance performance is affected by age in children and adolescents aged 6-18 years. More specifically, as maturation processes continue into adolescence it may be expected that adolescents exhibit better balance performance than children. Further, these performance differences may also affect associations between types of balance performance. More precisely, associations may be larger in children as compared to adolescents or young adults as the task-specificity of balance control may be less pronounced in less mature individuals. However, studies investigating associations between types of balance in youth were limited to certain types of balance (e.g., relationship between static and dynamic balance), single age-groups (e.g., children or adolescents), and used different balance tests which limits the comparability between different studies. Lastly, considering that balance seems to be affected by age in youth it is quite surprising that studies on the effectiveness of balance training in youth have paid little attention to the role of age. Indeed, only two studies [38, 39] have clearly addressed this issue but results were inconclusive.

Therefore, one research aim of this thesis was to scrutinise the role of age with respect to balance performance (i.e., STUDY I, II), concerning associations between types of balance in youth (i.e., STUDY II), and regarding balance training in youth (i.e., STUDY III). Two studies (i.e., STUDY I, II) investigated performance differences between individuals of different age groups, one study (i.e., STUDY II) analysed the effect of age on associations between types of balance in youth, and one study (i.e., STUDY III) verified whether a standardised balance training was equally effective in children and adolescents. Specifically, the following hypotheses were examined:

(1) Balance performance is better in adolescents compared to children (i.e., STUDY I, II).
(2) Relationships between types of balance performance are overall small in children, adolescents, and young adults but when relationships are compared between age groups, they are larger in younger (e.g., children) as compared to in older (e.g., adolescents, young adults) individuals (i.e., STUDY II).
(3) A standardised balance training will lead to improved balance performance in children and adolescents, with larger improvements in children (i.e., STUDY III).

2.6.2 Research questions examining the role of sex

Given that balance seems to be largely influenced by maturation in youth, it is reasonable to suggest that in this age group balance performance and the effectiveness of balance training may differ according to sex. More specifically, as maturation in girls is on average two years ahead of boys, structures involved in balance may be more developed in girls as compared to boys. Thus, with respect to balance, girls might possess an advantage over same-aged boys. Yet, studies on sex-related differences in balance performance in youth have reported mixed results and the influence of sex on the effectiveness of balance training has been largely disregarded so far. Therefore, two studies (i.e., STUDY I, IV) included in this doctoral thesis investigated the role of sex concerning balance in youth. One study (i.e., STUDY I) focused on the influence of sex on balance performance while the other study (i.e., STUDY IV) focused on sex-specific adaptations to balance practice and analysed how learning of a new balance task is affected by sex in children. In detail, the following hypotheses were examined:

(4) Girls show better balance performance compared to boys (i.e., STUDY I).
(5) Practicing a new balance task will lead to short-term (i.e., improved performance during practice trials) and long-term (i.e., improved performance in a delayed

retention and automation test) adaptations in children, which will be larger in girls as compared to boys (i.e., STUDY IV).

3 Materials and Methods

The following chapter outlines the materials and methods used within the framework of this doctoral thesis. It provides brief insights into the systematic literature search, participant's characteristics, the tests applied as well as the interventions conducted. For in-depth information on each of these aspects, the reader is referred to the respective full-text article (i.e., STUDY I-IV) at the end of each paragraph.

3.1 Systematic literature search

Within the scope of a systematic review and meta-analysis, a systematic literature search was performed in the databases PubMed, Web of Science, and SPORTDiscus to detect research articles on age- and sex-related differences in balance performance in youth. For this purpose, the following Boolean search strategy was developed and used: ((“balance performance” OR “postural control” OR “postural balance” OR postural stability OR balance test OR sensory integration OR gait OR functional reach OR balance function OR balance ability) AND (children OR adolescent OR youth OR girls OR boys OR development OR maturation)). The literature search was limited with respect to the publication date (i.e., 1960/01/01-2018/08/31), language (i.e., English), participant's age (i.e., 6-18 years), full-text original articles, and human species. Additionally, several inclusion (e.g., healthy individuals) and exclusion (e.g., patients, athletes) criteria were established beforehand. Extensive information on the systematic literature search is provided in the full text of STUDY I (cf. Chapter 4.1).

3.2 Participants

Overall, the samples of the age groups investigated (i.e., children, adolescents, young adults) consisted of healthy individuals without any neurological and/or musculoskeletal disease or other impairments that may have affected their ability to perform the tests applied. Further, only individuals naïve to the tests conducted were included. Written informed consent was obtained from all participants before the start of the respective study and parents' written assent was obtained for minors. Additionally, all participants were reminded that their participation was voluntary and that they were free to withdraw from the procedure at all times immediately before measurements began. The studies included in this doctoral dissertation were approved by the ethics committee of the Institute for Psychology of the University of Duisburg-Essen and carried out adhering to the latest version of the

Declaration of Helsinki [92]. Detailed information on participants' characteristics can be found in the Methods section of the respective research articles (cf. Chapters 4.2-4.4).

3.3 Anthropometric assessments

Anthropometric assessments included measuring body height, body mass, and leg length (LL) as well as calculating body mass index (BMI) and maturity offset. Body height was measured to the nearest 0.1 cm using a standardised portable stadiometer (seca 217, Basel, Switzerland), whereas body mass was assessed to the nearest 0.1 kg with a standardised digital scale (seca 803, Basel, Switzerland). By means of a tape measure, leg length was determined to the nearest 0.5 cm by gauging the distance from the distal end of the anterior superior iliac spine to the most distal point of the medial malleolus [80]. For accuracy, LL was measured twice and a third assessment was performed if the difference between the first two measurements was larger than 0.5 cm. In this case, the mean of all three trials was calculated. BMI was calculated by dividing body mass by the square of body height and expressed in kg/m^2. Lastly, to assess individual development maturity offset was calculated and expressed in years from peak height velocity (PHV) using the formulas provided by Moore [93]. Negative values indicate that the adolescents' growth spurt has not yet been reached, whereas positive values illustrate that individuals have already passed their maximal growth rate.

3.4 Assessment of balance performance

To answer the research questions of this doctoral dissertation, various balance tests were carried out. These will be presented separately for measures of static steady-state, dynamic steady-state, proactive, and reactive balance in the following paragraphs. All assessments were conducted in school or university gyms.

3.4.1 Assessment of static steady-state balance performance

Static steady-state balance was assessed using a one-legged stance on a three-dimensional force platform (AccuSway Optimize, AMTI, Watertown, MC, USA) [94]. Participants had to step on the platform with their non-dominant leg (i.e., stance leg when kicking a ball) without shoes, while the knee of the other leg was flexed to approximately 90° and were asked to stand as stable as possible for 30 s. Further, they were instructed to place their hands on the hips and to fixate a cross marked at eye level on the wall opposite to them, approximately one meter in front of the platform. Data was recorded at a sampling frequency of 100 Hz and filtered using a 4th-order Butterworth filter with a 10 Hz cut-off frequency.

The CoP path length [mm], which is the distance travelled by the CoP over the 30-s trial, as well as the deviated CoP-sway in anterior-posterior [A/P] and medio-lateral [M/L] directions were assessed and used for further analysis. Using similar procedures, Muehlbauer et al. [95] reported excellent intra- (ICC $\geq$ 0.76) as well as inter-session (ICC $\geq$ 0.79) reliability for these measures in healthy young adults except for inter-session reliability of M/L sway in men (ICC = 0.59). Furthermore, the pre- and post-test data of the control groups in STUDY III [42] were used to analyse test-retest reliability in children and adolescents, which proved to be excellent (ICC = 0.89).

3.4.2 Assessment of dynamic steady-state balance performance

To assess dynamic steady-state balance, a 10-m walk test [96] was conducted. In this test, participants had to walk a total distance of at least 12 meters including one meter to accelerate and decelerate, respectively. The 10-m zone as well as the 1-m sectors for acceleration and deceleration were marked with pylons. Participants were asked to cover the total distance of the walkway by walking “as fast as possible without running” while wearing sport shoes. The time needed to cover the middle 10-m distance was recorded using a standardised stopwatch. Furthermore, the cadence (e.g., number of steps) was noted. Subsequently, gait velocity (m/s) was calculated by dividing the distance covered (i.e., 10 m) by the time needed. This test has shown excellent test-retest reliability (ICC > 0.95) in healthy young adults [97] and gait velocity has shown excellent test-retest reliability in healthy adolescents (ICC $\geq$ 0.79) [98]. Additionally, test-retest reliability of the 10-m walk test in children and adolescents was analysed using the pre- and post-test data of the control groups in STUDY III [42], which proved to be excellent (ICC = 0.77) as well.

3.4.3 Assessment of proactive balance performance

Proactive balance performance was assessed using the lower quarter Y-balance test [99]. The Y-balance test kit (Functional Movement Systems, Chatham, USA) consists of a centralised stance platform to which three pipes are attached in anterior (AT), posteromedial (PM), and posterolateral (PL) directions. The pipes are marked with a scale of 1 cm increments and a movable reach indicator is situated above each pipe. During the test, participants have to stand on the centralised platform on one leg without shoes while reaching as far as possible in AT, PM, and PL directions with the other leg by moving the reach indicator without losing balance. The maximal reach distance per reach direction was noted and normalised to the participant’s leg length (LL) using the following equation:

Normalised Reach distance (%LL) = Maximal Reach distance / LL × 100. Further, a composite score (CS) was calculated using the following formula: CS (%LL) = ((AT + PM + PL)/(LL × 3)) × 100. The larger the normalised reach distance, the better is an individual's proactive balance performance. The Y-balance test has shown excellent inter- (ICC ≥ 0.99) and intra-rater (0.85 ≤ ICC ≤ 0.91) reliability [100] as well as excellent test-retest reliability (ICC > 0.75) in healthy adolescents [101].

3.4.4 Assessment of reactive balance performance

The Push-and-release test [102] was used to measure reactive balance performance. During the test, the participant was asked to lean backwards against the palms of the examiner's hands, which supported the individual at the scapulae. The examiner then removed his hands without warning so that the participant had to step backwards to avoid falling. To judge an individual's performance in the Push-and-release test the number of steps taken for recovery are counted and performance is rated as follows: 0 points = 1 step, 1 point = 2-3 small steps with independent recovery, 2 points = ≥ 4 steps with independent recovery, 3 points = multiple steps with assistance for recovery, 4 points = fall or unable to recover without assistance. The Push-and-release test has originally been developed for patients suffering from Parkinson's disease and Jacobs et al. [102] reported excellent inter-rater reliability (ICC ≥ 0.83) in a group of seniors with and without Parkinson's disease. Yet, the analysis of pre- and post-test data of the children's' and adolescents' control group in STUDY III [42], indicated a moderate (ICC = 0.43) test-retest reliability of the Push-and-release test in these age groups. Nevertheless, it is to the best of our knowledge currently the only field-based, easy-to-administer test to assess reactive balance performance.

3.5 Interventions

Two of the studies (i.e., STUDY III, IV) conducted for this doctoral dissertation included interventions. While one intervention consisted of a balance training program to investigate age-dependent adaptations of balance training in children and adolescents (i.e., STUDY III), the other intervention was designed to investigate the role of sex during the acquisition process and the learning of a new dynamic balance task in children (i.e., STUDY IV).

3.5.1 Balance training program

A standardised balance training program was conducted for five weeks during regular P.E. lessons at a school gym to investigate the influence of age on adaptations to balance training in children and adolescents. Training volume amounted to 135 minutes/week administered across two to three sessions per week. The training was supervised by the P.E. teacher and a graduate sports student. A 10-minute warm-up and a 5-minute cool-down marked the start and end of each session, respectively. In between, 5-8 balance exercises addressing static (i.e., standing exercises), dynamic (i.e., walking exercises), proactive (i.e., weight shifting while standing), and reactive (i.e., perturbed standing) balance were performed. The training program was designed according to the recommendations provided by Granacher and colleagues [103]. For details on the applied training regime please see the full text publication of STUDY III (cf. Chapter 4.3).

3.5.2 Acquisition and learning of a new dynamic balance task

To investigate the influence of sex on the acquisition and learning of a new dynamic balance task in children, participants were asked to balance on a stabilometer (Lafayette Instrument, Model 16030, Lafayette, LA, USA) on three consecutive days. This apparatus consists of a wooden platform (65 × 107 cm) that is mounted to a support frame via a centralised free spinning axis which allows a maximum deviation of 15 degrees from the horizontal plane to either side of the platform. For testing, participants were instructed to stand on the platform without shoes and try to keep it as stable and horizontal as possible (Fig. 4).

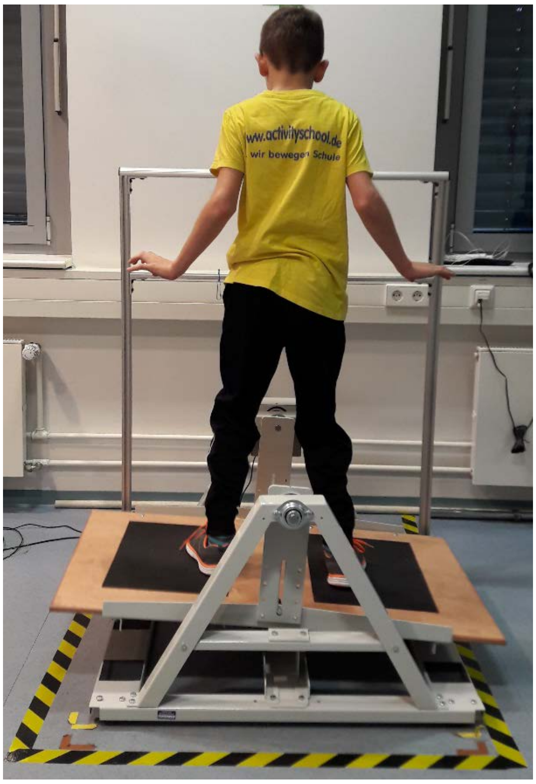

Figure 4. Illustration of a child balancing on the stability platform (stabilometer).

During the acquisition-phase, participants trained on the stabilometer on two consecutive days. Each day they performed seven 90-s-trials with 90-s-breaks in between. Knowledge of results (i.e., time in balance [s]) was given after each trial. On the third day, learning was assessed using a delayed retention test and an automation test. The retention test consisted of three trials which were identical to the acquisition-phase, yet no knowledge of results was provided. Afterwards the automation test, which involved three 90-s-trials of balancing on the stabilometer while simultaneously executing an additional motor task took place. The motor task required participants to hold two metal sticks in front of the body with elbows flexed to approximately 90° while balancing on the stabilometer. Both sticks were connected with two interlocked rings (Ø 4 cm) at one end and participants were advised to not let the rings touch each other throughout the trials, which were again separated by 90-s-rest periods. A digital timer measured the time in balance at a sampling rate of 25 Hz. A margin of ±3 degrees from the horizontal plane was allowed. The platform was connected to a laptop and platform position data was exported from PsymLab analysis soft-ware (Lafayette, LA, USA) and used to calculate the root-mean-square error (RMSE) of the platform. All sessions were carried out in a class room with only one participant and the experimenter being present at a time. Further details on the procedures can be found in the full text publication of STUDY IV (cf. Chapter 4.4)

3.6 Statistical Analyses

Within the scope of a systematic review and meta-analysis (i.e., STUDY I) standardised mean differences (*SMD*) were calculated to classify age- (i.e., children vs. adolescents) and sex-related (i.e., girls vs. boys) differences in balance performance in youth. The *SMD* is defined as the quotient of the “difference in mean outcome between groups” divided by the “standard deviation of the outcome among participants” [104]. First, *SMDs* were calculated for comparisons of age and/or sex within each study. Subsequently, these values were used to analyse differences between different types of balance performance (i.e., static, dynamic, proactive, reactive) according to age (i.e., children vs. adolescents) and sex (i.e., girls vs. boys). Therefore, the weighted mean *SMD* for comparisons between age groups and sex was computed using a random-effects meta-analysis. *SMDs* can be either positive or negative depending on the outcome measure. We defined positive values as indicating superior performances of adolescents compared to children and of girls compared to boys. Additionally, I^2-statistics were used to assess heterogeneity between studies and classified as being either trivial ($0\% \leq I^2 \leq 40\%$), moderate ($30\% \leq I^2 \leq 60\%$), substantial ($50\% \leq I^2 \leq 90\%$), or considerable ($75\% \leq I^2 \leq 100\%$) [104].

To assess relationships between types of balance, Pearson's correlation coefficients (*r*) were calculated and classified according to Vincent et al. [105] as indicating small- ($0 \leq r \leq 0.69$), medium- ($0.70 \leq r \leq 0.89$), or large-sized ($r \geq 0.90$) correlations. Further, correlation coefficients were compared between age groups (i.e., children vs. adolescents vs. young adults) using the formula $z = (z1\text{-}z2)/\sqrt{(1/(n1\text{-}3) + 1/(n2\text{-}3))}$ which has originally been developed by Cohen and Cohen [106]. In this regard, correlation coefficients were first transformed into a z-score using Fisher's r-to-z transformation [107] and thereafter statistically compared under consideration of the respective sample size [108].

In order to reveal the required sample sizes to obtain statistically significant results, a priori power analyses were calculated for the respective primary outcomes under specification of the effect size, type I error, type II error, number of groups, number of measurements and the correlation between measurements using G * Power [109]. Descriptive data analyses included the calculation of group means ± standard deviations for interval scaled data, whereas the median and interquartile range were computed for ordinal scaled data. Data was further tested for normal distribution using the Shapiro-Wilk test and Levene's test was used to test for homogeneity of variances. Analyses of variances (ANOVAs) were performed to compare performances of types of balance (i.e., static, dynamic, proactive, reactive) between age groups (e.g., children vs. adolescents), study groups (i.e., intervention vs. control) and/or sex (i.e., girls vs. boys) also taking the point of measurement (e.g., pre- vs. post-test) into account. If statistically significant main and/or interaction effects were observed, Bonferroni-adjusted post-hoc tests were calculated subsequently. Differences between pre- and post-test for ordinal scaled data were analysed using the Mann-Whitney-U test.

Cohen's *d* [110] was calculated as an effect size measure for *SMDs* and all interval scaled data and classified as representing small- ($0 \leq d \leq 0.49$), medium- ($0.50 \leq d \leq 0.79$), or large-sized ($d \geq 0.80$) effects. The pa.b.-value [111] was computed as an effect size measure for ordinal scaled data by dividing the Mann-Whitney-U statistics by the product of the respective sample sizes.

Statistical analyses for the systematic review with meta-analysis (i.e., STUDY I) were performed using Review Manager software version 5.3. For all other statistical analyses (i.e., STUDY II-IV) the Statistical Package for Social Sciences (SPSS) version 24.0 was used with the level of significance set at $p < .05$.

4 Main Results

In this chapter the main results of the studies conducted for this doctoral dissertation will be presented. Figure 5 provides an overview about the main findings with respect to differences between children and adolescents and boys and girls concerning balance performance and balance trainability.

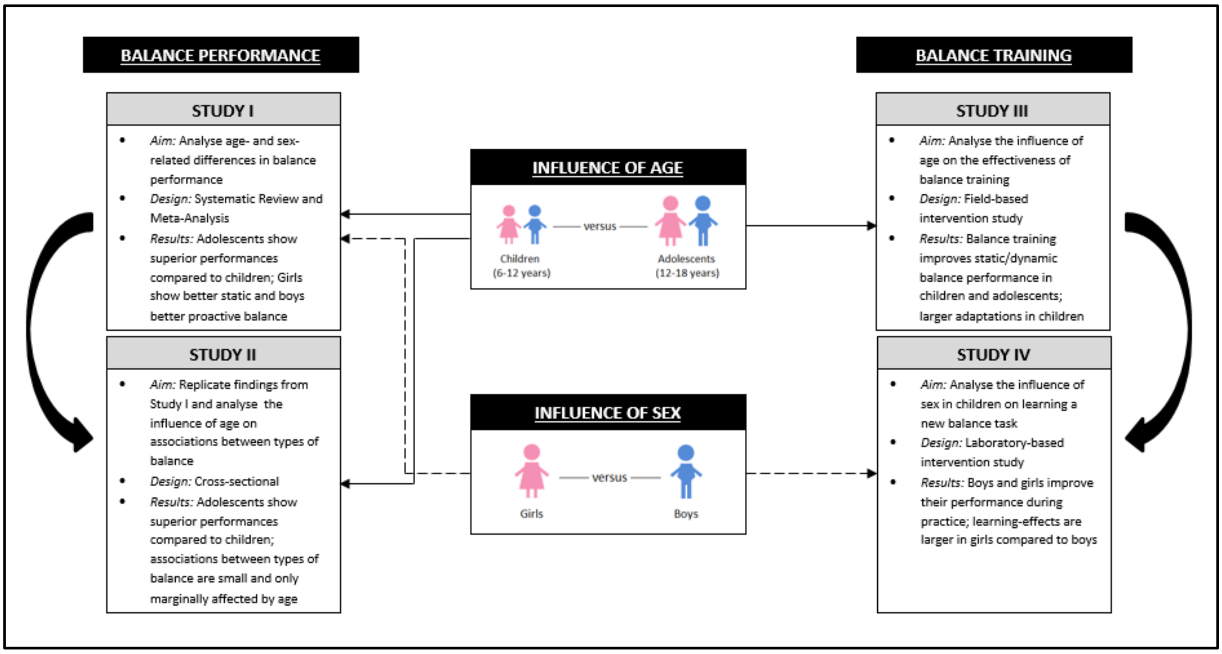

Figure 5. Illustration of the scientific framework of the presented doctoral dissertation specifying the main results of the conducted studies.

Details on the results of STUDY I-IV are provided in the following chapters 4.1-4.4 which include the presentation of each studies' key-points as well as the corresponding full-text article.

4.1 STUDY I – "*Age and sex differences in human balance performance from 6-18 years of age: A systematic review and meta-analysis*"

Aims and Hypotheses: The aim of STUDY I was to characterise and to quantify age- and sex-related differences in several variables of balance in youth. Hypotheses were that compared to children (6-12 years), adolescents (13-18 years) would show better performances in different types of balance (i.e., static, dynamic, proactive, reactive) and that girls (6-18 years) would exhibit superior balance performance compared to same aged boys (6-18 years).

Results and Conclusions: Twenty-one studies examining differences in balance performance between children and adolescents were included in the analysis. Compared to children, adolescents showed better static steady-state (*SMD* = 1.20), dynamic steady-state (*SMD* = 0.26), and proactive (*SMD* = 0.28) balance performance. No studies meeting the inclusion criteria were found for reactive balance performance. Analysis of the results of 25 studies investigating sex-related differences in balance performance in youth revealed better static steady-state balance performance in girls compared to boys (*SMD* = 0.33), almost no sex-related difference regarding dynamic steady-state balance performance (*SMD* = -0.02), and superior proactive balance performance of boys compared to girls (*SMD* = -0.15). No study comparing reactive balance performance between girls and boys met the inclusion criteria. The development of postural control continues into adolescence which may also have an impact on the effectiveness of balance training. Further, depending on the type of balance investigated, sex-related differences have to be considered when assessing balance performance in girls and boys of the same chronological age.

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RESEARCH ARTICLE

Age and sex differences in human balance performance from 6-18 years of age: A systematic review and meta-analysis

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Abstract

Background

The process of growing leads to inter-individual differences in the timing of growth, maturational, and developmental processes during childhood and adolescence, also affecting balance performance in youth. However, differences in balance performance by age and sex in youth have not been systematically investigated yet.

Objective

The objective of the present study was to characterize and quantify age- and sex-related differences in balance performance in healthy youth.

Methods

A computerized systematic literature search was performed in the electronic databases PubMed, Web of Science, and SPORTDiscus. To be applicable for analysis, studies had to report at least one measure of static steady-state, dynamic steady-state, proactive or reactive balance in healthy children (6–12 years) and/or adolescents (13–18 years). Coding of the studies was done according to the following criteria: age, sex, and balance outcome. Study quality was assessed using the Appraisal tool for Cross-Sectional Studies. Weighted standardized mean differences were calculated and classified according to their magnitude.

Results

Twenty-one studies examined age-related differences in balance performance. A large effect for measures of static steady-state balance (SMD_{ba} = 1.20) and small effects for proxies of dynamic steady-state (SMD_{ba} = 0.26) and proactive balance (SMD_{ba} = 0.28) were found; all in favor of adolescents. Twenty-five studies investigated sex-related differences in balance performance. A small-sized effect was observed for static steady-state balance (SMD_{bs} = 0.33) in favor of girls and for dynamic steady-state (SMD_{bs} -0.02) and proactive

balance (SMD_{bs} = -0.15) in favor of boys. Due to a lack of studies, no analysis for measures of reactive balance was performed.

Conclusions

Our systematic review and meta-analysis revealed better balance performances in adolescents compared to children, irrespective of the measure considered. Sex-related differences were inconsistent. These findings may have implications for example in terms of trainability of balance in youth that should be investigated in future studies.

Introduction

Balance is generally referred to as the ability to keep the body's center of mass within the base of support [1]. Integrating sensory information from visual, sensorimotor, and vestibular receptors and producing adequate muscle synergies, enables humans to achieve and maintain balance under static conditions where the base of support and the ground remain stationary (e.g., standing) as well as under dynamic conditions where the center of mass and the base of support shift (e.g., walking). According to Shumway-Cook and Woollacott [2], balance can further be subdivided into four types of balance hardly associated with each other: static steady-state balance (i.e., maintaining a steady position while standing/sitting), dynamic steady-state balance (i.e., maintaining a steady position while walking), proactive balance (i.e., anticipation of a predicted postural disturbance), and reactive balance (i.e., compensation of an unpredicted postural disturbance).

Depending on the measured variable, balance performance shows a U-shaped (e.g., postural sway) or inverted U-shaped (e.g, gait velocity) relationship with age across the lifespan illustrating increasing performance in youth, peak performance in young adults, and decreasing performance in seniors [3]. The development of balance performance throughout youth has been an area of particular research interest as it may assist in the early identification of diseases and/or disorders, designing training regimes, or understanding deteriorating balance performance in older adults and seniors. As indicated by for instance decreasing postural sway [4, 5] and increasing gait speed [6, 7], balance performance reportedly improves from early childhood onwards. The underlying developmental processes have been investigated in detail and it has been shown that physical factors (e.g., growth, weight gain) only marginally influence balance performance in youth [8, 9]. In fact, improved sensory integration [1, 10], the task-specific use of different postural control strategies [11, 12], and progressive brain maturation [13, 14] particularly account for improvements in balance performance in youth. However, there is still conflicting evidence whether these developments lead to differences in balance performance between school-aged children (6–12 years) and adolescents (13–18 years) in favor of the first or the latter. Some authors found adult-like blance performance in children at the end of the first decade of life (i.e., 7-10-year-olds [15], 11-13-year-olds [16]), indicating equal or even better balance performances of children compared to adolescents. Other studies [10, 17], however, reported better balance performances of adolescents compared to children. Hence, the true extent of age-related differences in balance performance in youth remains debatable.

Besides age-related differences in balance performance, research has also focused on sex-related differences. For example, in adults, better performances of females compared to males have been reported [18, 19], although some evidence suggests that these might be related to anthropometric differences [20]. Similarly, there is conflicting evidence with respect to sex-related differences in balance performance in youth. Several studies [17, 21, 22] reported better balance performance in girls compared to same-aged boys, which has been attributed to improved sensory integration [17], advanced neuromuscular development [21], and the use of more adult-like postural control strategies [22]. Furthermore, it has been suggested that compared to boys, girls are less hyperactive [10] and more attentive during balancing tasks [17]. However, there are also studies showing girls and boys to perform equally well in terms of balance performance [23, 24]. Consequently, it is still questionable, if and to what extent sex-related differences in balance performance in youth exist.

Although balance performance in youth has been studied extensively over the past decades, evidence regarding age- and sex-related differences is rather contradictory. Certainly, knowledge about the development of balance and maturation of involved systems in terms of differences between children and adolescents and between girls and boys may assist clinicians and practitioners in the early identification of developmental disorders and diseases or in the development of specific training regimes. Meta-analyses provide the highest level of evidence on the evidence pyramid [25] and, to the best of our knowledge, no study has systematically investigated age- and sex-related differences in balance performance in youth yet. Thus, the aim of this systematic literature review and meta-analysis was to characterize and quantify age- and sex-related differences in several variables of balance in healthy youth. We expected better balance performances in adolescents compared to children and in girls compared to boys.

Methods

Search of literature

A systematic literature search in the electronic databases PubMed, Web of Science, and SPORTDiscus was performed using the following Boolean search strategy: (("balance performance" OR "postural control" OR "postural balance" OR postural stability OR balance test OR sensory integration OR gait OR functional reach OR balance function OR balance ability) AND (children OR adolescent OR youth OR girls OR boys OR development OR maturation)). Additionally, the search was limited to publication date (1960/01/01-2018/08/31), age (6–18 years), English language, full-text original articles, and human species. Moreover, reference lists of included articles and relevant review articles were checked and analyzed to identify other studies potentially suitable for inclusion.

Criteria for selection

Table 1 summarizes the applied selection criteria. To be eligible for inclusion, studies had to meet the following criteria: (a) participants were healthy; (b) participants were aged between

Table 1. Selection criteria.

Category	Inclusion criteria	Exclusion criteria
Population	healthy children (6–12 years) and/or adolescents (13–18 years)	patients, athletes
Measurement	balance during single-task	balance during dual- and/or supra-postural task
Outcome	at least one measure of static steady-state, dynamic steady-state, proactive, and/or reactive balance	reported data did not allow for calculation of effect sizes; author(s) did not respond to our inquiries
Study design	cross-sectional studies	intervention studies not reporting pre-intervention data for healthy controls matching the other inclusion criteria

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six and 18 years; (c) at least one balance parameter was registered in the study; (d) results were reported either for children (6–12 years) and adolescents (13–18 years) or for girls and boys or for children and adolescents as well as for girls and boys. While most children start attending school at six years having achieved certain developmental and motor milestones (e.g., running, hopping) [26], pre-schoolers are even more heterogenous in terms of inter-individual development and were therefore excluded from this study. The other exclusion criteria were as follows: (a) participants were exclusively athletes, patients, and/or people with diseases; (b) reported data did not allow for calculation of effect sizes [27, 28]; (c) study authors did not reply to our inquiries to send original data [8, 29, 30]; (d) balance parameters were measured on an absolute scale (e.g., number of errors during single-leg stance); (e) balance performance was measured under dual- and/or supra-postural task conditions.

Studies comparing balance performance of athletes, patients and/or people with diseases to that of healthy controls were included, if they reported relevant data for control group(s), which allowed for comparisons of balance performance between age groups and/or sex within the controls. Similarly, interventional studies were also included, if pre-intervention data of balance performance was reported, enabling us to analyze age- and/or sex-related differences. Study eligibility was assessed by two independent reviewers (SS, TM). A third vote (RK) was obtained, if the two reviewers disagreed about the eligibility of a study for inclusion. If studies reported results for age groups overlapping with our categories, we grouped them according to the predominating age. For example, Condon and Cremin [31] reported data for 12-15-year-olds, which we classified as data of adolescents as only the 12-year-olds would represent children, while the 13-, 14- and 15-year-olds represent adolescents.

Study coding

Each included study was coded for the following criteria: number of participants, sex, and age. Due to the inconsistent findings on whether balance performance is adult-like in ten- to twelve-year-olds and according to previously established developmental models classifying adolescence into the age period of either 11.5–16 years [32], 12–18 years in girls and 14–18 years in boys [33], or 10–19 years in girls and 12–20 years in boys [34], the age-range of 6–12 years was defined for children, while 13-18-year-olds represent adolescents in our study. Balance performance was classified into the following categories, as suggested by Shumway-Cook and Woollacott [2]: static steady-state balance (i.e., maintaining a static position while standing), dynamic steady-state balance (i.e., maintaining a steady position while walking), proactive balance (i.e., anticipation of a predicted postural disturbance), and reactive balance (i.e., compensation of a postural disturbance). As some studies reported several variables within one outcome category, we prioritized the most commonly reported measure for each category to reduce heterogeneity between studies. Regarding static steady-state balance, highest priority was given to CoP displacements during single-leg stance with eyes open. Gait velocity during walking at preferred speed was used with reference to dynamic steady-state balance. In terms of proactive balance, highest relevance was given to the distance in the FR, while CoP displacements during perturbed single-leg stance were defined as most representative for reactive balance. If studies reported other measures as proxies of the aforementioned categories, alternative outcome(s) were used depending on the administered balance test and recorded parameter(s). Table 2 lists the preferred and alternative outcome(s) for each balance category.

Study quality

The Appraisal tool for Cross-Sectional Studies [35] was used for quality assessment of included studies. It consists of 20 questions addressing study design, study quality, and risk of bias,

Table 2. Preferred and alternative outcome(s). *BESS* Balance error scoring system, *CoP* Center of Pressure, *FR* Functional-Reach test, *LOS* Limits of stability *SOT* Sensory Organization Test, *TUG* Timed up and go test.

Category	Preferred outcome	Alternative outcome(s)
Static steady-state balance	CoP displacements during single-leg stance	time in balance SOT BESS Balance Index
Dynamic steady-state balance	gait speed during walking	cadence body sway body accelerations LOS
Proactive balance	reach distance during FR	TUG Star excursion balance test CoP displacements during self-perturbed stance Timed up and down stairs test
Reactive balance	CoP displacements during perturbed stance	-

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which have to be answered with "yes", "no", or "do not know". Seven questions refer to quality of reporting (1, 4, 10, 11, 12, 16, 18) and seven to study design (2, 3, 5, 8, 17, 19, 20). Another six questions (6, 7, 9, 13, 14, 15) relate to a possible risk of bias. Three questions (7, 13, 14) asking for potential non-responders were excluded from our analysis as this criterion was not applicable for the vast majority of included studies. Quality assessment was performed by two independent reviewers (SS, TM). If the respective reviewers did not reach a consensus, evaluation from a third expert (RK) was obtained.

Statistical analyses

Age (i.e., children vs. adolescents) and sex (i.e., boys vs. girls) differences in balance performances were assessed using standardized mean difference (SMD), which is defined as follows:

$$\mathrm{SMD} = \frac{\text{Difference in mean outcome between groups}}{\text{Standard deviation of outcome among participants}}$$

Two studies only reported confidence intervals (CI) [36] or standard errors (SE) [37] instead of standard deviations (SD). According to the Cochrane Handbook for Systematic Reviews of Interventions [38] we used the following formula to calculate SD from CI:

$$\mathrm{SD} = \sqrt{\mathrm{N}}\ \mathrm{x}\ \frac{(\text{upper limit} - \text{lower limit})}{\text{t value}}$$

where *N* is the number of subjects within a group, *upper* and *lower limit* the particular CI and *t value* is defined by the length of the CI and the degrees of freedom. To derive SD from SE we used the following formula [38]:

$$\mathrm{SD} = \mathrm{SE}\ \mathrm{x}\ \sqrt{\mathrm{N}}$$

where SE is the particular standard error and N is the number of subjects within a group. At first, SMDs and SDs were calculated for differences in balance performance by age group (i.e., children vs. adolescents) and sex (i.e., girls vs. boys) for comparisons within each study. Subsequently, computed SMDs and SDs were used to assess differences between components of balance (i.e., static/dynamic steady-state, proactive, and reactive balance) by age (SMD_{ba}) and sex (SMD_{bs}). Calculation of weighted mean SMD_{ba} and SMD_{bs} was done using a random-effects meta-analysis in Review Manager version 5.3. SMD_{ba} and SMD_{bs} can be negative or positive depending on the outcome measure. For example, less sway during a balance task would yield a negative SMD, whereas a longer time in balance would result in a positive SMD, although both represent good balance performance. Consistent with our hypotheses, positive SMD_{ba}/SMD_{bs} indicate better balance performance of adolescents compared to children and of girls compared to boys, respectively. According to Cohen [39], values for SMD_{ba}/SMD_{bs} of $0 \leq 0.49$ indicate small effects, values of $0.50 \leq 0.79$ indicate medium effects, and values of ≥ 0.80 indicate large effects. I^2 and Chi^2-statistics were used to assess heterogeneity between studies. In agreement with Deeks et al. [40], heterogeneity was classified as being either trivial ($0\% \leq I^2 \leq 40\%$), moderate ($30\% \leq I^2 \leq 60\%$), substantial ($50\% \leq I^2 \leq 90\%$), or considerable ($75\% \leq I^2 \leq 100\%$).

Results

Fig 1 illustrates the process of the systematic literature search. The systematic literature search revealed 27,653 studies potentially suitable for analysis. After screening titles, reading abstracts, and removing duplicates a total of 38 articles remained suitable for inclusion. Further five articles were identified from the reference lists of included articles and relevant reviews and found to be eligible for inclusion. Therefore, 43 studies were included in the final analysis. Eighteen studies reported data for balance performance of children and adolescents, 22 studies reported data for balance performance of boys and girls, and three studies reported data for both comparisons.

Description of included studies

Table 3 shows the characteristics of the 21 included studies reporting measures of balance performance in children and adolescents. Twelve studies [5, 10, 17, 31, 41–48] reported variables of static steady-state balance, two studies [49, 50] analyzed outcomes of dynamic steady-state balance, and six studies [36, 37, 51–54] examined proxies of proactive balance. One study analyzed static and dynamic steady-state balance as well as reactive balance [55]. Data of a total of 9,716 subjects of whom 8,168 were categorized as children and 1,548 were grouped as adolescents were eligible for analysis. Age ranged from 6–13 years in children and from 12–19 years in adolescents.

Characteristics of the 25 included studies comparing measures of balance performance in boys and girls are shown in Table 4. Twelve studies [22, 24, 45, 56–64] examined variables of static steady-state balance, five studies [49, 65–68] analyzed outcomes of dynamic steady-state balance, four studies [23, 52, 69, 70] examined outcomes of proactive balance, two studies [21, 71] reported proxies of both static and dynamic steady-state balance, and two studies [72, 73] scrutinized measures of static steady-state and proactive balance. No study reported outcomes of reactive balance. Eligible for analysis were the data of a total of 10,723 subjects aged between six and 19 years of whom 5,143 were males and 5,580 were females.

Quality of the included studies

Quality assessment revealed that the majority of included studies complied with most of the criteria of the Appraisal tool for Cross-Sectional studies. In detail, 40 out of 43 studies fulfilled ≥4 out of 7 criteria regarding the quality of study reports, 43 out of 43 studies fulfilled ≥4 out of 7 criteria addressing the design of studies, and concerning risk of bias ≥2 out of 3 criteria were met by 40 out of the 43 included studies (S1 Table). Thus, the majority of studies met the criteria above average.

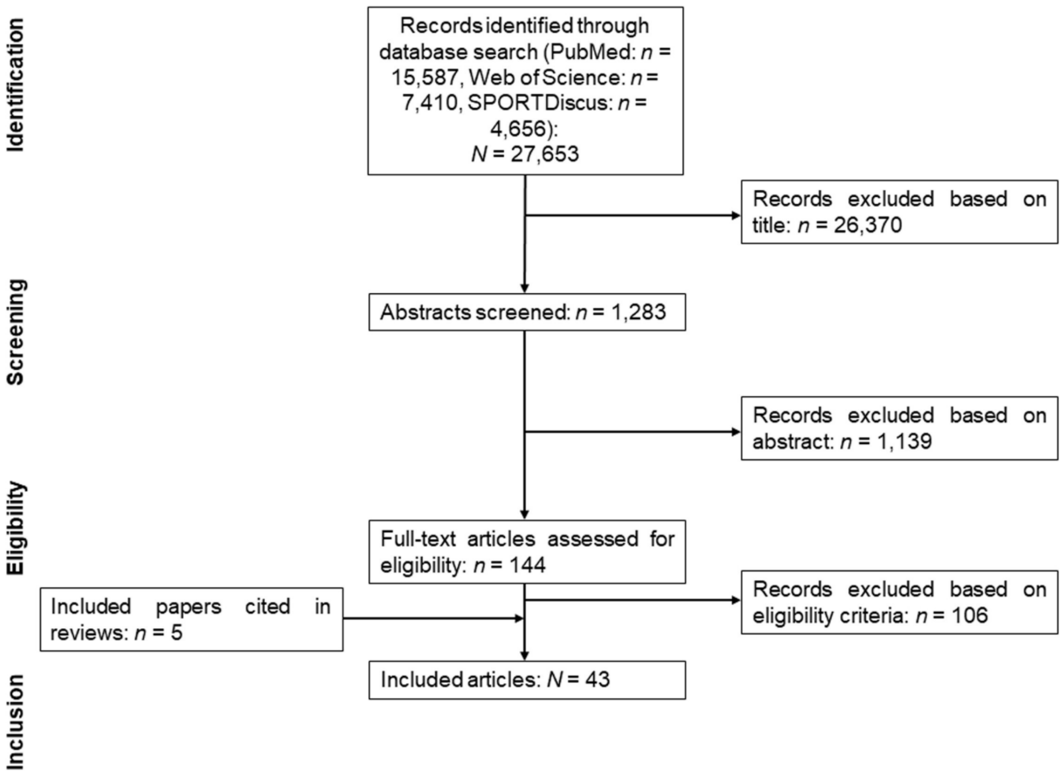

Fig 1. Flow chart illustrating the different phases of the search and selection.

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Age differences

The comparisons of static steady-state balance performance between children and adolescents is shown in Fig 2. Weighted mean SMD_{ba} amounted to 1.20 (I^2 = 86%, Chi^2 = 326.87, df = 45, $p < .001$, 13 studies, 46 comparisons) suggesting a large effect in favor of adolescents. Moreover, weighted mean SMD_{ba} amounted to 0.26 for outcomes of dynamic steady-state balance (I^2 = 59%, Chi^2 = 67.89, df = 28, $p < .001$, three studies, 29 comparisons) and to 0.28 for variables of proactive balance (I^2 = 91%, Chi^2 = 250.85, df = 22, $p < .001$, six studies, 23 comparisons), respectively, indicating small-sized effects in favor of adolescents (Figs 3 and 4). Heterogeneity between studies was considerable for static steady-state and proactive balance and substantial in terms of dynamic steady-state balance. No SMD_{ba} was calculated for reactive balance as our search did not identify the required minimum of two studies.

Sex differences

As illustrated in Fig 5, weighted mean SMD_{bs} amounted to 0.33 (I^2 = 23%, Chi^2 = 42.76, df = 33, p = 0.12, sixteen studies, 34 comparisons) for measures of static steady-state balance,

Table 3. Included studies examining age differences (children vs. adolescents) in balance performance in youth.

References	No. of subjects; sex; age [years (range or mean ± SD)]; n	Balance test parameter; outcome	Results SMD_{bu} (95% CI)
An et al. [41]	39; F (15), M (24); 7–14	sSSB: one-legged stance, dominant leg, firm surface, eyes open; time in balance (60 s maximum)	7-9- vs. 12-14-year-olds: 0.92 (0.25, 1.59)
	7-9-year-olds; 19		
	12-14-year-olds; 20		
Barozzi et al. [42]	289; F (115), M (174); 6–14	sSSB: 52-s two-legged stance, barefoot, eyes open, firm surface; sway velocity (mm/s)	6- vs. 13-year-olds: 2.12 (1.43, 2.81)
			7- vs. 13-year-olds: 1.82 (1.29, 2.35)
	6-year-olds; 20		8- vs. 13-year-olds: 1.05 (0.56, 1.54)
	7-year-olds; 43		9- vs. 13-year-olds: 0.93 (0.40, 1.46)
	8-year-olds; 38		10- vs. 13-year-olds: 0.92 (0.45, 1.39)
	9-year-olds; 27		11- vs. 13-year-olds: 1.73 (1.14, 2.32)
	10-year-olds; 45		12- vs. 13-year-olds: 0.44 (-0.01, 0.89)
	11-year-olds; 29		
	12-year-olds; 41		6- vs. 14-year-olds: 1.97 (1.07, 2.87)
			7- vs. 14-year-olds: 2.07 (1.29, 2.85)
	13-year-olds; 35		8- vs. 14-year-olds: 1.38 (0.65, 2.11)
	14-year-olds; 11		9- vs. 14-year-olds: 1.19 (0.43, 1.95)
			10- vs. 14-year-olds: 1.37 (0.66, 2.08)
			11- vs. 14-year-olds: 2.61 (1.69, 3.53)
			12- vs. 14-year-olds: 0.74 (0.05, 1.43)
Chivers et al. [43]	993; N/A; 10–14	sSSB: one-legged stance, both legs, eyes open, eyes closed; total time in balance (s)	10- vs. 14-year-olds: 0.63 (0.49, 0.77)
	10-year-olds: 507		
	14-year-olds: 486		
Condon & Cremin [31]	495; F (275), M (220); 6–15	sSSB: one-legged stance, dominant leg, firm surface, eyes open; time in balance (s)	6-7- vs. 12-15-year-olds: 2.33 (2.02, 2.64)
			8-9- vs. 12-15-year-olds: 1.37 (1.12, 1.62)
	6-7-year-olds; 125		10-11- vs. 12-15-year-olds: 0.36 (0.09, 0.63)
	8-9-year-olds; 152		
	10-11-year-olds; 78		
	12-15-year-olds; 140		
Donahoe et al. [36]	95; F (53), M (42); 7–15	PB: FR; mean reach (cm)	7-8- vs. 13-15-year-olds: 0.80 (0.07, 1.53)
			9-10- vs. 13-15-year-olds: 0.81 (-0.03, 1.65)
	7-8-year-olds; 36		11-12- vs. 13-15-year-olds: -0.06 (-0.77, 0.65)

(*Continued*)

Table 3. (Continued)

References	No. of subjects; sex; age [years (range or mean ± SD)]; n	Balance test parameter; outcome	Results SMD_{ba} (95% CI)
	9-10-year-olds; 15		
	11-12-year-olds; 34		
	13-15-year-olds; Mid-PHV; 10		
Habib et al. [51]	160; F (80), M (80); 6–13	PB: FR; mean reach (cm)	6- vs. 13-year-olds: 1.01 (0.34, 1.68)
			7- vs. 13-year-olds: 1.14 (0.45, 1.83)
	6-year-olds; 20		8- vs. 13-year-olds: 0.53 (-0.12, 1,18)
	7-year-olds; 20		9- vs. 13-year-olds: 0.85 (0.18, 1.52)
	8-year-olds; 20		10- vs. 13-year-olds: 0.71 (0.06, 1.36)
	9-year-olds; 20		11- vs- 13-year-olds: 0.28 (-0.35, 0.91)
	10-year-olds; 20		12- vs- 13-year-olds: 0.24 (-0.39, 0.87)
	11-year-olds; 21		
	12-year-olds; 20		
	13-year-olds; 19		
Hirabayashi & Iwasaki [10]	79; F (39), M (40); 7–15	sSSB: SOT; total equilibrium score	7-8- vs. 14-15-year-olds: 1.71 (0.95, 2.47)
			9-10- vs. 14-15-year-olds: 1.37 (0.68, 2.06)
	7-8-year-olds; 18		11-13- vs. 14-15-year-olds: 0.30 -0.33, 0.93)
	9-10-year-olds; 22		
	11-13-year-olds; 20		
	14-15-year-olds; Mid-PHV; 19		
Itzkowitz et al. [52]	1295; F (743), M (552); 6–13	PB: TUG; time (s)	6- vs.13-year-olds: -0.29 (-0.60, 0.02)
			7- vs.13-year-olds: -0.31 (-0.62, 0.00)
	6-year-olds; 244		8- vs.13-year-olds: -0.68 (-1.01, -0.35)
	7-year-olds; 221		9- vs.13-year-olds: -0.91 (-1.24, -0.58)
	8-year-olds; 197		10- vs.13-year-olds: -0.89 (-1.22, -0.56)
	9-year-olds; 203		11- vs.13-year-olds: -0.70 (-1.07, -0.33)
	10-year-olds; 180		12- vs.13-year-olds: -0.44 (-0.79, -0.09)
	11-year-olds; 95		
	12-year-olds; 110		
	13-year-olds; Mid-PHV; 45		
Johnson et al. [44]	33; N/A; 10.35 ± 3.28	sSSB: one-legged stance, dominant leg, eyes open; sway velocity in anterior/posterior directions (mm/s)	8-12- vs. 13-18-year-olds: 0.84 (0.04, 1.64)
	8-12-year-olds; 19		
	13-18-year-olds; 14		

(Continued)

Table 3. (Continued)

References	No. of subjects; sex; age [years (range or mean ± SD)]; n	Balance test parameter; outcome	Results SMD$_{ba}$ (95% CI)
Khanna et al. [45]	100; F (35), M (65); 12.47 ± 2.01	sSSB: BESS; total score	10-13- vs. 14-17-year-olds: 0.07 (-0.34, 0.48)
	10-13-years-olds; 68		
	14-17-years-olds; 32		
Menkveld et al. [50]	60; N/A; 7–16	dSSB: gait analysis using Electrodynogram and force data collector, walking at self-selected speed; cadence	7-8- vs. 13-14-year-olds: 2.25 (1.19, 3.31)
			9-10- vs. 13-14-year-olds: 0.91 (0.07, 1.75)
	7-8-year-olds; 12		11-12- vs. 13-14-year-olds: 0.50 (-0.32, 1.32)
	9-10-year-olds; 12		
	11-12-year-olds; 12		7-8- vs. 15-16-year-olds: 2.59 (1.45, 3.73)
			9-10- vs. 15-16-year-olds: 1.17 (0.29, 2.05)
	13-14-year-olds; 12		11-12- vs- 15-16-year-olds: 1.01 (0.15, 1.87)
	15-16-year-olds; 12		
Müller et al. [49]	5,215; F (2,771), M (2,444); 6–15	dSSB: gait analysis using VICON, force plates and photo electronic barrier; gait velocity (m/s)	6- vs. 13-year-olds: 0.32 (0.16, 0.48)
	6-year-olds; 977		7- vs. 13-year-olds: 0.28 (0.12, 0.44)
	7-year-olds; 834		8- vs. 13-year-olds: 0.16 (0.00, 0.32)
	8-year-olds; 819		9- vs. 13-year-olds: 0.24 (0.08, 0.40)
	9-year-olds; 711		10- vs. 13-year-olds: 0.15 (-0.01, 0.31)
	10-year-olds; 687		11- vs. 13- year-olds: 0.11 (-0.07, 0.29)
	11-year-olds; 437		12- vs. 13-year-olds: 0.09 (-0.09, 0.27)
	12-year-olds; 364		
			6- vs. 14-year-olds: 0.31 (0.11, 0.51)
	13-year-olds; 197		7- vs. 14-year-olds: 0.27 (0.07, 0.47)
	14-year-olds; 109		8- vs. 14-year-olds: 0.15 (-0.05, 0.35)
	15-year-olds; 80		9- vs. 14-year-olds: 0.23 (0.03, 0.43)
			10- vs. 14-year-olds: 0.14 (-0.06, 0.34)
			11- vs. 14- year-olds: 0.10 (-0.12, 0.32)
			12- vs. 14-year-olds: 0.08 (-0.14, 0.30)
			6- vs. 15-year-olds: 0.40 (0.16, 0.64)
			7- vs. 15-year-olds: 0.36 (0.12, 0.60)

(Continued)

Table 3. (Continued)

References	No. of subjects; sex; age [years (range or mean ± SD)]; n	Balance test parameter; outcome	Results SMD$_{ba}$ (95% CI)
			8- vs. 15-year-olds: 0.24 (0.00, 0.48)
			9- vs. 15-year-olds: 0.33 (0.09, 0.57)
			10- vs. 15-year-olds: 0.24 (0.00, 0.48)
			11- vs. 15- year-olds: 0.19 (-0.05, 0.43)
			12- vs. 15-year-olds: 0.18 (-0.06, 0.42)
Nicolini-Panisson & Donadio [53]	385; F (199), M (186); 6–18	PB: TUG; time (s)	6-9- vs. 14-18-year-olds: 0.82 (0.57, 1.07)
	6-9-year-olds; 130		10-13- vs. 14-18-year-olds: 0.71 (0.46, 0.96)
	10-13-year-olds; 129		
	14-18-year-olds; 126		
Sheldon [5]	39; F (22), M (17); 6–19	sSSB: 60-s two-legged stance, eyes closed; number of squares penetrated by tracing	6-9- vs. 15-19-year-olds: 2.38 (1.52, 3.24)
	6-9-year-olds; 14		
	15-19-year-olds; 25		
Steindl et al. [17]	100; F (50), M (50); 7–16	sSSB: SOT; total equilibrium score	7-8- vs. 13-14-year-olds: 1.68 (0.95, 2.41)
			9-10- vs. 13-14-year-olds 1.03 (0.36, 1.70)
	7-8-year-olds; 20		11-12- vs. 13-14-year-olds: -0.20 (-0.83, 0.43)
	9-10-year-olds; 20		
	11-12-year-olds; 20		7-8- vs. 15-16-year-olds: 2.69 (1.81, 3.57)
			9-10- vs. 15-16-year-olds: 1.84 (1.10, 2.58)
	13-14-year-olds; 20		11-12- vs. 15-16-year-olds: 0.55 (-0.08, 1.18)
	15-16-year-olds; 20		
Tringali et al. [46]	56; F (25), M (31); 6–15	sSSB: 4 x 12.8-s two-legged stance in Romberg position, eyes open on a force platform; sway velocity (mm/s)	6-7- vs. 12-13-year-olds: 3.22 (1.91, 4.53)
			8-9- vs. 12-13-year-olds: 0.36 (-0.52, 1.24)
	6-7-year-olds; 14		10-11- vs. 12-13-year-olds: 0.06 (-0.80, 0.92)
	8-9-year-olds; 11		
	10-11-year-olds; 12		6-7- vs. 14-15-year-olds: 6.02 (3.98, 8.06)
			8-9- vs. 14-15-year-olds: 2.87 (1.58, 4.16)
	12-13-year-olds; 9		10-11- vs. 14-15-year-olds: 1.61 (0.61, 2.61
	14-15-year-olds; 10		
Volkman et al. [54]	80; F (40), M(40); 7–16	PB: FR; mean reach (cm)	7-8- vs. 15-16-year-olds: 1.99 (1.32, 2.66)
			11-12- vs. 15-16-year-olds: 0.45 (-0.10, 1.00)

(Continued)

Table 3. (Continued)

References	No. of subjects; sex; age [years (range or mean ± SD)]; n	Balance test parameter; outcome	Results SMD$_{ba}$ (95% CI)
	7-8-year-olds; 29		
	11-12-year-olds; 26		
	15-16-year-olds; 25		
Walchli et al. [55]	77; F (38), M (39); 6–15	sSSB: 15-s Romberg stance, eyes open on a force platform; total sway path (cm)	sSSB
			6-7- vs. 14-15-year-olds: 1.25 (0.64, 1.86)
	6-7-year-olds: 25		11-12- vs. 14-15-year-olds: 0.37 (-0.18, 0.92)
	11-12-year-olds: 27		
		dSSB: 15-s two-legged stance, eyes open on a spinning top (Pedalo Kreisel) placed on force platform; total sway path (cm)	dSSB
	14-15-year-olds: 25		6-7- vs. 14-15-year-olds: 1.18 (0.57, 1.79)
			11-12- vs. 14-15-year-olds: 0.36 (-0.19, 0.91)
		RB: 15-s two-legged stance, eyes open on swinging platform (Posturomed); total sway path (cm) assessed using VICON	RB
			6-7- vs. 14-15-year-olds: 1.12 (0.52, 1.71)
			11-12- vs. 14-15-year-olds: 0.10 (-0.45, 0.64)
Wolff et al. [47]	74; N/A; 7–18	sSSB: 10 x 30-s two-legged stance, barefoot, eyes open; sway velocity (mm/s)	7-8- vs. 13-14-year-olds: 0.64 (-0.12, 1.40)
			9-10- vs. 13-14-year-olds: 0.56 (-0.20, 1.32
	7-8-year-olds; 16		11-12- vs. 13-14-year-olds: 0.11 (-0.65, 0.87)
	9-10-year-olds; 16		
	11-12-year-olds; 15		7-8- vs. 15-18-year-olds: 1.05 (0.29, 1.81)
			9-10- vs. 15-18-year-olds: 0.91 (0.17, 1.65)
	13-14-year-olds; 12		11-12- vs. 15-18-year-olds: 0.38 (-0.35, 1.11)
	15-18-year-olds; 15		
Zaino et al. [37]	27; F (14), M (13); 8–14	PB: Timed up and down stairs test; time (s)	8-10- vs. 13-14-year-olds: 1.09 (0.11, 2.07)
			11-12- vs. 13-14-year-olds: 0.24 (-0.86, 1.34)
	8-10-year-olds; 14		
	11-12-year-olds; 6		
	13-14-year-olds; 7		
Zumbrunn et al. [48]	32; F (17), M (15); 8–18	sSSB: 5 x 5-s one-legged stance, dominant and non-dominant leg, eyes open; sway velocity (mm/s)	8-12- vs. 13-18-year-olds: 1.07 (0.31, 1.83)
	8-12-year-olds; 19		
	13-18-year-olds; 13		

BESS Balance error scoring system, *dSSB* dynamic steady-state balance, *F* female, *FR* Functional-Reach Test, *M* male, *N/A* not available, *PB* proactive balance, *SD* standard deviation, SMD_{ba} between-subject standardized mean difference (i.e., children versus adolescents), *SOT* Sensory Organization Test, *sSSB* static steady-state balance, *TUG* Timed up and go test.

https://doi.org/10.1371/journal.pone.0214434.t003

Table 4. Included studies examining sex differences (boys vs. girls) in balance performance in youth.

References	No. of subjects; sex; age [years (range or mean ± SD)]; maturation; n	Balance test parameter; outcome	Results SMD_{bs} (95% CI)
Arévalo-Mora et al. [56]	187; F (97), M (90); 11.15 ± 1.24	sSSB: 60-s one-legged stance, barefoot, eyes open on beam (3 cm wide, 20 cm above floor); time in balance (s)	0.09 (-0.20, 0.38)
Butz et al. [23]	140; F (70), M (70); 6–12	PB: TUG; time (s)	6-year-olds: 0.57 (-0.33, 1.47)
			7-year-olds: 0.26 (-0.62, 1.14)
	6-year-olds; F (10), M (10)		8-year-olds: -0.51 (-1.41, 0.39)
	7-year-olds; F (10), M (10)		9-year-olds: 0.50 (-0.40, 1.40)
	8-year-olds; F (10), M (10)		10-year-olds: -0.19 (-1.07, 0.69)
	9-year-olds; F (10), M (10)		11-year-olds: -0.51 (-1.41, 0.39)
	10-year-olds; F (10), M (10)		12-year-olds: 0.51 (-0.39, 1.41)
	11-year-olds; F (10), M (10)		
	12-year-olds; F (10), M (10)		
Davies & Rose [57]	60; F (30), M (30); 7–18	sSSB: one-legged stance, dominant leg, eyes open, firm surface; time in balance (20 s maximum)	Pre-PHV: -0.42 (-1.30, 0.46)
			Mid-PHV: -0.42 (-1.30, 0.46)
	Females		Post-PHV: 0.42 (-0.46, 1.30)
	Pre-PHV; 9.55 ± 0.72; 10		
	Mid-PHV; 12.65 ± 1.36; 10		
	Post-PHV; 16.14 ± 1.09; 10		
	Males		
	Pre-PHV; 11.28 ± 1.26; 10		
	Mid-PHV; 14.51 ± 1.32; 10		
	Post-PHV; 17.74 ± 0.85; 10		
Deshmukh et al. [69]	350; F (175), M (175); 6–12	PB: FR; mean reach (cm)	6-year-olds: -0.67 (-1.24, -0.10)
			7-year-olds: -0.76 (-1.33, -0.19)
	6-year-olds; F (25), M (25)		8-year-olds: 0.06 (-0.49, 0.61)
	7-year-olds; F (25), M (25)		9-year-olds: -0.39 (-0.96, 0.18)
	8-year-olds; F (25), M (25)		10-year-olds: -0.16 (-0.71, 0.39)
	9-year-olds; F (25), M (25)		11-year-olds: -0.14 (-0.69, 0.41)
	10-year-olds; F (25), M (25)		12-year-olds: 0.68 (0.11, 1.25)
	11-year-olds; F (25), M (25)		
	12-year-olds; F (25), M (25)		
Dufek et al. [65]	56; F (23), M (33); 14.7 ± 1.5	dSSB: gait analysis using GAITRite system; gait velocity during preferred walking speed (m/s)	0.17 (-0.36, 0.70)
Eguchi & Takada [21]	47; F (23), M (24); 8–11	sSSB: 2 x 30-s one-legged stance, barefoot, dominant leg; mean synthesized	sSSB

(*Continued*)

Table 4. (Continued)

References	No. of subjects; sex; age [years (range or mean ± SD)]; maturation; n	Balance test parameter; outcome	Results SMD_{bs} (95% CI)
		root mean square (S-RMS) of body accelerations	9-year-olds: 1.08 (0.18, 1.98)
	sSSB		11-year-olds: 0.80 (-0.10, 1.70)
	9-year-olds; F (11), M (11)		
	11-year-olds; F (10), M (11)	dSSB: 2 x 5 m walking, barefoot self-selected speed; mean synthesized root mean square (S-RMS) of body accelerations	dSSB
			9-year-olds: 0.48 (-0.32, 1.28)
	dSSB		11-year-olds: 0.33 (-0.51, 1.17)
	9-year-olds; F (12), M (13)		
	11-year-olds: F (11), M (11)		
Geldhof et al. [71]	99; F (58), M (41); 9.8 ± 0.5	sSSB: modified clinical test of sensory interaction on balance; sway velocity (°/sec)	sSSB
			0.59 (0.18, 1.00)
		dSSB: LOS; sway velocity (°/sec)	dSSB
			-0.04 (-0.43, 0.35)
Holm & Vøllestad [58]	368; F (184), M (184); 7–12	sSSB: one-legged stance on KAT 2000 system; Balance Index	7-year-olds: 0.70 (0.13, 1.27)
			8-year-olds: 0.07 (-0.46, 0.60)
	7-year-olds; F(19), M (40)		9-year-olds: 0.43 (-0.06, 0.92)
	8-year-olds; F (26), M (29)		10-year-olds: 0.06 (-0.41, 0.53)
	9-year-olds; F (39), M (29)		11-year-olds: 0.82 (0.29, 1.35)
	10-year-olds; F (40), M (29)		12-year-olds: 0.37 (-0.14, 0.88)
	11-year-olds; F (29), M (29)		
	12-year-olds; F (31), M (28)		
Holm et al. [66]	360; F (179), M (181); 7–12	dSSB: gait analysis using GAITRite; cadence (step/min) at normalized gait velocity of 1.5 m/s	7-year-olds: 0.00 (-0.59, 0.59)
			8-year-olds: -0.46 (-1.03, 0.11)
	7-year-olds: 52; F (16), M (36)		9-year-olds: 0.23 (-0.24, 0.70)
	8-year-olds: 48; F (21), M (27)		10-year-olds: -0.10 (-0.59, 0.39)
	9-year-olds: 69; F (38), M (31)		11-year-olds: -0.40 (-0.95, 0.15)
	10-year-olds: 68; F (39), M (29)		12-year-olds: 0.00 (-0.47, 0.47)
	11-year-olds: 53; F (28), M (25)		
	12-year-olds: 70; F (37), M (33)		
Itzkowitz et al. [52]	1295; F (743), M (552); 6–13	PB: TUG; time (s)	6-year-olds: -0.06 (-0.31, 0.19)
			7-year-olds: -0.03 (-0.30, 0.24)

(Continued)

Table 4. (Continued)

References	No. of subjects; sex; age [years (range or mean ± SD)]; maturation; n	Balance test parameter; outcome	Results SMD$_{bs}$ (95% CI)
	6-year-olds; F (120), M (124)		13-year-olds: 0.14 (-0.57, 0.85)
	7-year-olds; F (129), M (92)		8-year-olds: -0.44 (-0.71, -0.17)
	8-year-olds; F (98), M (99)		9-year-olds: -0.58 (-0.87, -0.29)
	9-year-olds; F (130), M (73)		10-year-olds: -0.26 (-0.55, 0.03)
	10-year-olds; F (112), M (68)		11-year-olds: -0.50 (-0.91, -0.09)
	11-year-olds; F (45), M (50)		12-year-olds: -0.05 (-0.44, 0.34)
	12-year-olds; F (74), M (36)		
	13-year-olds; F (35), M (10)		
Khanna et al. [45]	100; F (35), M (65); 12.47 ± 2.01	sSSB: BESS; total score	0.19 (-0.22, 0.60)
Laguna Nieto et al. [73]	18; F (9), M (9); N/A	sSSB: 10-s one-legged stance on a force platform, right leg, barefoot, eyes open; total sway area (mm^2)	sSSB
			1.77 SE 0.58 (0.63, 2.91)
		PB: moving CoP towards specified targets as fast as possible; accuracy (%)	PB
			0.41 SE 0.48 (-0.53, 1.35)
Lee & Lin [59]	709; F (344), M (365); 9.61 ± 0.68	sSSB: 3 x 10-s one-legged stance, barefoot, alternately on left and right leg, eyes open on a force platform; mean radius of CoP (cm)	0.25 (0.19, 0.41)
Libardoni et al. [24]	165; F (82), M (83); 8–12	sSSB: SOT, balance score in condition one (two-legged stance, eyes open)	8-year-olds: -0.51 (-1.49, 0.47)
			9-year-olds: 0.18 (-0.58, 0.94)
			10-year-olds: 0.69 (-0.21, 1.59)
			11-year-olds: -0.14 (-1.16, 0.88)
			12-year-olds: -0.53 (-1.43, 0.37)
McKay et al. [72]	160; F (80), M (80); 10–19	sSSB: one-legged stance, eyes closed; time in balance (maximum 10 s)	sSSB: 0.21 (-0.10, 0.52)
		PB: star excursion balance test; distance reached in posteromedial direction (% of leg length)	PB: -0.24 (-0.55, 0.07)
Michelotti et al. [60]	52; F (24), M (28); 13.73 ± 1.20 (mean age of	sSSB: 51.2-s two-legged stance on a force platform; sway velocity (mm/s)	0.37 (-0.18, 0.92)
	matched intervention group)		
Mickle et al. [61]	84; F (47), M (37); 8–12	sSSB: 30-s one-legged stance, dominant leg, eyes open; body sway assessed via Lord sway-meter	0.53 (0.10, 0.96)
Müller et al. [49]	5,215; F (2,771), M (2,444); 6–15	dSSB: gait analysis using VICON, force plates and photo electronic barrier; gait velocity (m/s)	6-year-olds: 0.11 (-0.01, 0.23)
			7-year-olds: 0.04 (-0.10, 0.18)
	6-year-olds; F (522), M (455)		8-year-olds: -0.08 (-0.22, 0.06)
	7-year-olds; F (426), M (408)		9-year-olds: -0.13 (-0.29, 0.03)

(Continued)

Table 4. (Continued)

References	No. of subjects; sex; age [years (range or mean ± SD)]; maturation; n	Balance test parameter; outcome	Results SMD_{bs} (95% CI)
	8-year-olds; F (434), M (385)		10-year-olds: -0.10 (-0.26, 0.06)
	9-year-olds; F (391), M (320)		11-year-olds: -0.06 (-0.26, 0.14)
	10-year-olds; F (372), M (315)		12-year-olds: -0.09 (CI -0.29, 0.11)
	11-year-olds; F (237), M (200)		13-year-olds: -0.01 (-0.28, 0.26)
	12-year-olds; F (184), M (180)		14-year-olds: -0.19 (-0.56, 0.18)
	13-year-olds; F (99), M (98)		15-year-olds: 0.13 (-0.32, 0.58)
	14-year-olds; F (57), M (52)		
	15-year-olds; F (49), M (31)		
Öberg et al. [67]	54; F (27), M (27); 10–19	dSSB: gait analysis, walking at normal speed; gait velocity (cm/s)	10-14-year-olds: -1.43 (-2.35, -
			0.51)
	10-14-year-olds: F (12), M (12)		15-19-year-olds: -0.70 (-1.44, 0.04)
	15-19-year-olds: F (15), M (15)		
Peterson et al. [62]	154; F (74), M (80); 6–12	sSSB: SOT; total equilibrium score	6-year-olds: 0.97 (-0.48, 2.42)
			7-year-olds: 0.60 (-0.18, 1.38)
	6-year-olds; F (4), M (5)		8-year-olds: 0.25 (-0.44, 0.94)
	7-year-olds; F (14), M (12)		9-year-olds: 0.38 (-0.29, 1.05)
	8-year-olds; F (14), M (21)		10-year-olds: -0.20 (-1.08, 0.68)
	9-year-olds; F (20), M (16)		11-year-olds: 0.76 (-0.22, 1.74)
	10-year-olds; F (9), M (11)		12-year-olds: 0.02 (-1.29, 1.33)
	11-year-olds; F (7), M (11)		
	12-year-olds; F (5), M (4)		
Sheehan & Katz [64]	65; F (36), M (29); 6–9	sSSB: 6 x 20-s stance (one-legged stance, eyes open, firm surface; one-legged stance eyes closed, firm surface; one-legged stance, eyes open, foam surface; tandem stance, eyes open, firm surface; tandem stance, eyes closed, firm surface; tandem stance, eyes open, foam surface); total CoP path (mm)	0.61 (0.10, 1.12)
Sheehan & Katz [63]	61; F (28), M (33); N/A	sSSB: 6 x 20-s stance (one-legged stance, eyes open, firm surface; one-legged stance eyes closed, firm surface; one-legged stance, eyes open, foam surface; tandem stance, eyes open, firm surface; tandem stance, eyes closed, firm surface; tandem stance, eyes open, foam surface); total CoP path (mm)	0.49 (-0.02, 1.00)
Smith et al. [22]	26; F (9), M (17); 8–12	sSSB: 3 x 30-s two-legged stance, barefoot; sway velocity (mm/s)	0.55 (-0.27, 1.37)
Thevenon et al. [68]	382; F (154), M (228); 6–12	dSSB: gait analysis using GAITRite; gait velocity (cm/s)	6-year-olds: -0.12 (-0.65, 0.41)
			7-year-olds: 0.32 (-0.25, 0.89)
	6-year-olds: 61; F (20), M (41)		8-year-olds: -0.35 (-0.90, 0.20)

(Continued)

Table 4. (Continued)

References	No. of subjects; sex; age [years (range or mean ± SD)]; maturation; n	Balance test parameter; outcome	Results SMD_{bs} (95% CI)
	7-year-olds: 53; F (20), M (33)		9-year-olds: 0.22 (-0.31, 0.75)
	8-year-olds: 56; F (22), M (34)		10-year-olds: 0.33 (-0.22, 0.88)
	9-year-olds: 57; F (27), M (30)		11-year-olds: 0.43 (-0.14, 1.00)
	10-year-olds: 54; F (20), M (34)		12-year-olds: 0.87 (0.26, 1.48)
	11-year-olds: 54; F (20), M (34)		
	12-year-olds: 47; F (25), M (22)		
Yuksel et al. [70]	280; F (152), M (128); 6–12	PB: FR; mean reach (cm)	6-year-olds: 0.48 (-0.15, 1.11)
			7-year-olds: 0.42 (-0.23, 1.07)
	6-year-olds; F (20), M (20)		8-year-olds: -0.51 (-1.14, 0.12)
	7-year-olds; F (25), M (15)		9-year-olds: 0.00 (-0.63, 0.63)
	8-year-olds; F (20), M (20)		10-year-olds: -0.21 (-0.84, 0.42)
	9-year-olds; F (22), M (18)		11-year-olds: -0.15 (-0.78, 0.48)
	10-year-olds; F (21), M (19)		12-year-olds: -0.40 (-1.03, 0.23)
	11-year-olds; F (23), M (17)		
	12-year-olds; F (21), M (19)		

BESS Balance error scoring system, *CoP* center of pressure, *dSSB* dynamic steady-state balance, *F* female, *FR* Functional-Reach Test, *LOS* limits of stability, *M* male, *N/A* not available, *PB* proactive balance, *PHV* peak height velocity, *SD* standard deviation, *SMDbs* between-subject standardized mean difference (i.e., boys versus girls), *SOT* Sensory Organization Test, *sSSB* static steady-state balance, *TUG* Timed up and go test.

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indicating a small effect in favor of girls. In contrast and as shown in Figs 6 and 7, small-sized effects in favor of boys were found for variables of dynamic steady-state and proactive balance as SMD_{bs} amounted to -0.02 (I^2 = 40%, Chi^2 = 47.03, df = 28, p = 0.01, seven studies, 29 comparisons) and -0.15 (I^2 = 44%, Chi^2 = 53.43, df = 30, p = 0.005, six studies, 31 comparisons), respectively. Heterogeneity between studies was trivial regarding static steady-state balance and moderate in terms of dynamic steady-state and proactive balance. Given that our literature search did not identify the required minimum of two studies on reactive balance no SMD_{bs} was calculated for that particular parameter. Changes in SMD_{bs} when calculated for children and adolescents separately were neglectable (data not shown).

Discussion

To the best of our knowledge, the present systematic review and meta-analysis is the first which characterized and quantified age and sex differences in balance performance in youth. Analyses of the data of 43 studies revealed consistently better balance performances in adolescents compared to children irrespective of the variable considered, supporting our first hypothesis. Largest differences were found for measures of static steady-state balance, while SMD_{ba} were considerably smaller for measures of dynamic steady-state and proactive balance.

Study or Subgroup	Std. Mean Difference	SE	Children Total	Adolescents Total	Weight	Std. Mean Difference IV, Random, 95% CI
An et al. [2009] 7-9 vs 12-14yrs	0.92	0.34	19	20	2.2%	0.92 [0.25, 1.59]
Barozzi et al. [2014] 10 vs 13yrs	0.92	0.24	45	35	2.5%	0.92 [0.45, 1.39]
Barozzi et al. [2014] 10 vs 14yrs	1.37	0.36	45	11	2.2%	1.37 [0.66, 2.08]
Barozzi et al. [2014] 11 vs 13yrs	1.73	0.3	29	35	2.4%	1.73 [1.14, 2.32]
Barozzi et al. [2014] 11 vs 14yrs	2.61	0.47	29	11	1.9%	2.61 [1.69, 3.53]
Barozzi et al. [2014] 12 vs 13yrs	0.44	0.23	41	35	2.5%	0.44 [-0.01, 0.89]
Barozzi et al. [2014] 12 vs 14yrs	0.74	0.35	41	11	2.2%	0.74 [0.05, 1.43]
Barozzi et al. [2014] 6 vs 13yrs	2.12	0.35	20	35	2.2%	2.12 [1.43, 2.81]
Barozzi et al. [2014] 6 vs 14yrs	1.97	0.46	20	11	1.9%	1.97 [1.07, 2.87]
Barozzi et al. [2014] 7 vs 13 yrs	1.82	0.27	43	35	2.4%	1.82 [1.29, 2.35]
Barozzi et al. [2014] 7 vs 14yrs	2.07	0.4	43	11	2.1%	2.07 [1.29, 2.85]
Barozzi et al. [2014] 8 vs 13yrs	1.05	0.25	38	35	2.5%	1.05 [0.56, 1.54]
Barozzi et al. [2014] 8 vs 14yrs	1.38	0.37	38	11	2.2%	1.38 [0.65, 2.11]
Barozzi et al. [2014] 9 vs 13yrs	0.93	0.27	27	35	2.4%	0.93 [0.40, 1.46]
Barozzi et al. [2014] 9 vs 14yrs	1.19	0.39	27	11	2.1%	1.19 [0.43, 1.95]
Chivers et al. [2013]	0.63	0.07	507	486	2.8%	0.63 [0.49, 0.77]
Condon & Cremin [2014] 10-11 vs 12-15yrs	0.36	0.14	78	140	2.7%	0.36 [0.09, 0.63]
Condon & Cremin [2014] 6-7 vs 12-15yrs	2.33	0.16	125	140	2.7%	2.33 [2.02, 2.64]
Condon & Cremin [2014] 8-9 vs 12-15yrs	1.37	0.13	152	140	2.7%	1.37 [1.12, 1.62]
Hirabayashi & Iwasaki [1995] 11-13 vs 14-15yrs	0.3	0.32	20	19	2.3%	0.30 [-0.33, 0.93]
Hirabayashi & Iwasaki [1995] 7-8 vs 14-15yrs	1.71	0.39	18	19	2.1%	1.71 [0.95, 2.47]
Hirabayashi & Iwasaki [1995] 9-10 vs 14-15yrs	1.37	0.35	22	19	2.2%	1.37 [0.68, 2.06]
Johnson et al. [2014] 8-12 vs 13-18yrs	0.84	0.41	12	14	2.1%	0.84 [0.04, 1.64]
Khanna et al. [2015] 10-13 vs 14-17yrs	0.07	0.21	68	32	2.6%	0.07 [-0.34, 0.48]
Sheldon [1963] 6-9 vs 15-19yrs	2.38	0.44	14	25	2.0%	2.38 [1.52, 3.24]
Steindl et al. [2006] 11-12 vs 13-14yrs	-0.2	0.32	20	20	2.3%	-0.20 [-0.83, 0.43]
Steindl et al. [2006] 11-12 vs 15-16yrs	0.55	0.32	20	20	2.3%	0.55 [-0.08, 1.18]
Steindl et al. [2006] 7-8 vs 13-14yrs	1.68	0.37	20	20	2.2%	1.68 [0.95, 2.41]
Steindl et al. [2006] 7-8 vs 15-16yrs	2.69	0.45	20	20	1.9%	2.69 [1.81, 3.57]
Steindl et al. [2006] 9-10 vs 13-14yrs	1.03	0.34	20	20	2.2%	1.03 [0.36, 1.70]
Steindl et al. [2006] 9-10 vs 15-16yrs	1.84	0.38	20	20	2.1%	1.84 [1.10, 2.58]
Tringali et al. [2017] 10-11 vs 12-13yrs	0.06	0.44	12	9	2.0%	0.06 [-0.80, 0.92]
Tringali et al. [2017] 10-11 vs 14-15yrs	1.61	0.51	12	10	1.8%	1.61 [0.61, 2.61]
Tringali et al. [2017] 6-7 vs 12-13yrs	3.22	0.67	14	9	1.4%	3.22 [1.91, 4.53]
Tringali et al. [2017] 6-7 vs 14-15yrs	6.02	1.04	14	10	0.8%	6.02 [3.98, 8.06]
Tringali et al. [2017] 8-9 vs 12-13yrs	0.36	0.45	11	9	1.9%	0.36 [-0.52, 1.24]
Tringali et al. [2017] 8-9 vs 14-15yrs	2.87	0.66	11	10	1.4%	2.87 [1.58, 4.16]
Wolff et al. [1998] 11-12 vs 13-14yrs	0.11	0.39	15	12	2.1%	0.11 [-0.65, 0.87]
Wolff et al. [1998] 11-12 vs 15-18yrs	0.38	0.37	15	15	2.2%	0.38 [-0.35, 1.11]
Wolff et al. [1998] 7-8 vs 13-14yrs	0.64	0.39	16	12	2.1%	0.64 [-0.12, 1.40]
Wolff et al. [1998] 7-8 vs 15-18yrs	1.05	0.39	16	15	2.1%	1.05 [0.29, 1.81]
Wolff et al. [1998] 9-10 vs 13-14yrs	0.56	0.39	16	12	2.1%	0.56 [-0.20, 1.32]
Wolff et al. [1998] 9-10 vs 15-18yrs	0.91	0.38	16	15	2.1%	0.91 [0.17, 1.65]
Wälchli et al. [2018] sSSB 11-12 vs 14-15yrs	0.37	0.28	27	25	2.4%	0.37 [-0.18, 0.92]
Wälchli et al. [2018] sSSB 6-7 vs 14-15yrs	1.25	0.31	25	25	2.3%	1.25 [0.64, 1.86]
Zumbrunn et al. [2011] 8-12 vs 13-18yrs	1.07	0.39	19	13	2.1%	1.07 [0.31, 1.83]
Total (95% CI)			**1880**	**1697**	**100.0%**	**1.20 [0.98, 1.43]**

Heterogeneity: Tau² = 0.45; Chi² = 326.87, df = 45 (P < 0.00001); I² = 86%
Test for overall effect: Z = 10.69 (P < 0.00001)

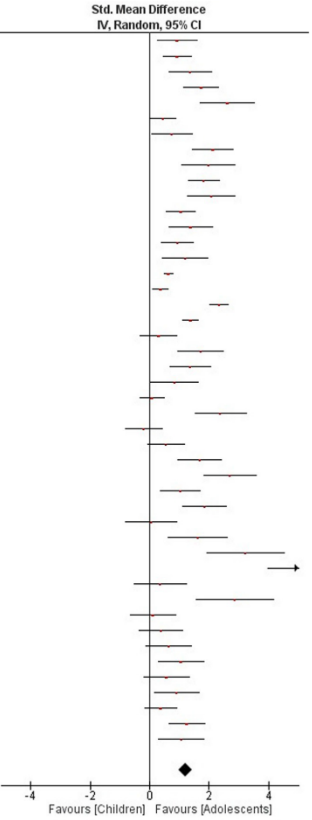

Fig 2. Differences in measures of static steady-state balance by age (children vs. adolescents). *CI* confidence interval, *df* degrees of freedom, *SE* standard error, *IV* inverse variance.

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In terms of sex differences in balance performance, SMD_{bs} revealed only small-sized effects. Girls showed better performances than boys in measures of static steady-state balance but were outperformed by boys in proactive balancing tasks. Even though boys showed slightly better performances than girls in terms of dynamic steady-state balance, this difference probably is functionally irrelevant due to the low SMD_{bs} of -0.02. Based on these results, we can only partially confirm our second hypothesis that girls show better balance performances compared to same-aged boys.

Age differences in balance performance in youth

Our analysis revealed better balance performances of adolescents compared to children in terms of static steady-state, dynamic steady-state, and proactive balance. These findings support our first hypothesis that adolescents exhibit better postural control than children and

Study or Subgroup	Std. Mean Difference	SE	Children Total	Adolescents Total	Weight	Std. Mean Difference IV, Random, 95% CI
Menkveld et al. [1988] 11-12 vs 13-14yrs	0.5	0.42	12	12	0.7%	0.50 [-0.32, 1.32]
Menkveld et al. [1988] 11-12 vs 15-16yrs	1.01	0.44	12	12	0.6%	1.01 [0.15, 1.87]
Menkveld et al. [1988] 7-8 vs 13-14yrs	2.25	0.54	12	12	0.4%	2.25 [1.19, 3.31]
Menkveld et al. [1988] 7-8 vs 15-16yrs	2.59	0.58	12	12	0.4%	2.59 [1.45, 3.73]
Menkveld et al. [1988] 9-10 vs 13-14yrs	0.91	0.43	12	12	0.6%	0.91 [0.07, 1.75]
Menkveld et al. [1988] 9-10 vs 15-16yrs	1.17	0.45	12	12	0.6%	1.17 [0.29, 2.05]
Müller et al. [2013] 10 vs 13yrs	0.15	0.08	687	197	5.2%	0.15 [-0.01, 0.31]
Müller et al. [2013] 10 vs 14yrs	0.14	0.1	687	109	4.5%	0.14 [-0.06, 0.34]
Müller et al. [2013] 10 vs 15yrs	0.24	0.12	687	80	3.9%	0.24 [0.00, 0.48]
Müller et al. [2013] 11 vs 13yrs	0.11	0.09	437	197	4.9%	0.11 [-0.07, 0.29]
Müller et al. [2013] 11 vs 14yrs	0.1	0.11	437	109	4.2%	0.10 [-0.12, 0.32]
Müller et al. [2013] 11 vs 15 yrs	0.19	0.12	437	80	3.9%	0.19 [-0.05, 0.43]
Müller et al. [2013] 12 vs 13yrs	0.09	0.09	364	197	4.9%	0.09 [-0.09, 0.27]
Müller et al. [2013] 12 vs 14yrs	0.08	0.11	364	109	4.2%	0.08 [-0.14, 0.30]
Müller et al. [2013] 12 vs 15yrs	0.18	0.12	364	80	3.9%	0.18 [-0.06, 0.42]
Müller et al. [2013] 6 vs 13yrs	0.32	0.08	977	197	5.2%	0.32 [0.16, 0.48]
Müller et al. [2013] 6 vs 14yrs	0.31	0.1	977	109	4.5%	0.31 [0.11, 0.51]
Müller et al. [2013] 6 vs 15yrs	0.4	0.12	977	80	3.9%	0.40 [0.16, 0.64]
Müller et al. [2013] 7 vs 13yrs	0.28	0.08	834	197	5.2%	0.28 [0.12, 0.44]
Müller et al. [2013] 7 vs 14yrs	0.27	0.1	834	109	4.5%	0.27 [0.07, 0.47]
Müller et al. [2013] 7 vs 15yrs	0.36	0.12	834	80	3.9%	0.36 [0.12, 0.60]
Müller et al. [2013] 8 vs 13yrs	0.16	0.08	819	197	5.2%	0.16 [0.00, 0.32]
Müller et al. [2013] 8 vs 14yrs	0.15	0.1	819	109	4.5%	0.15 [-0.05, 0.35]
Müller et al. [2013] 8 vs 15yrs	0.24	0.12	819	80	3.9%	0.24 [0.00, 0.48]
Müller et al. [2013] 9 vs 13yrs	0.24	0.08	711	197	5.2%	0.24 [0.08, 0.40]
Müller et al. [2013] 9 vs 14yrs	0.23	0.1	711	109	4.5%	0.23 [0.03, 0.43]
Müller et al. [2013] 9 vs 15yrs	0.33	0.12	711	80	3.9%	0.33 [0.09, 0.57]
Wälchli et al. [2018] dSSB 11-12 vs 14-15yrs	0.36	0.28	27	25	1.3%	0.36 [-0.19, 0.91]
Wälchli et al. [2018] dSSB 6-7 vs 14-15yrs	1.18	0.31	25	25	1.1%	1.18 [0.57, 1.79]
Total (95% CI)			**14611**	**2824**	**100.0%**	**0.26 [0.19, 0.33]**

Heterogeneity: Tau² = 0.02; Chi² = 67.89, df = 28 (P < 0.0001); I² = 59%
Test for overall effect: Z = 7.26 (P < 0.00001)

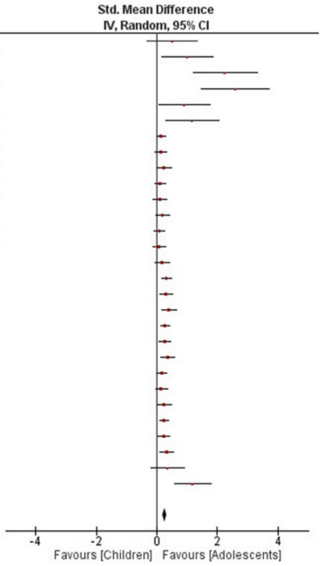

Fig 3. Differences in measures of dynamic steady-state balance by age (children vs. adolescents). *CI* confidence interval, *df* degrees of freedom, *SE* standard error, *IV* inverse variance.

https://doi.org/10.1371/journal.pone.0214434.g003

Study or Subgroup	Std. Mean Difference	SE	Children Total	Adolescents Total	Weight	Std. Mean Difference IV, Random, 95% CI
Donahoe et al. [1994] 11-12 vs 13-15yrs	-0.06	0.36	34	10	4.1%	-0.06 [-0.77, 0.65]
Donahoe et al. [1994] 7-8 vs 13-15yrs	0.8	0.37	36	10	4.0%	0.80 [0.07, 1.53]
Donahoe et al. [1994] 9-10 vs 13-15yrs	0.81	0.43	15	10	3.8%	0.81 [-0.03, 1.65]
Habib et al. [1999] 10 vs 13yrs	0.71	0.33	20	19	4.2%	0.71 [0.06, 1.36]
Habib et al. [1999] 11 vs 13yrs	0.28	0.32	21	19	4.3%	0.28 [-0.35, 0.91]
Habib et al. [1999] 12 vs 13yrs	0.24	0.32	20	19	4.3%	0.24 [-0.39, 0.87]
Habib et al. [1999] 6 vs 13yrs	1.01	0.34	20	19	4.2%	1.01 [0.34, 1.68]
Habib et al. [1999] 7 vs 13yrs	1.14	0.35	20	19	4.1%	1.14 [0.45, 1.83]
Habib et al. [1999] 8 vs 13yrs	0.53	0.33	20	19	4.2%	0.53 [-0.12, 1.18]
Habib et al. [1999] 9 vs 13yrs	0.85	0.34	20	19	4.2%	0.85 [0.18, 1.52]
Itzkowitz et al. [2016] 10 vs 13yrs	-0.89	0.17	180	0	4.8%	-0.89 [-1.22, -0.56]
Itzkowitz et al. [2016] 11 vs 13yrs	-0.7	0.19	95	45	4.8%	-0.70 [-1.07, -0.33]
Itzkowitz et al. [2016] 12 vs 13yrs	-0.44	0.18	110	45	4.8%	-0.44 [-0.79, -0.09]
Itzkowitz et al. [2016] 6 vs 13yrs	-0.29	0.16	244	45	4.8%	-0.29 [-0.60, 0.02]
Itzkowitz et al. [2016] 7 vs 13yrs	-0.31	0.16	221	45	4.8%	-0.31 [-0.62, 0.00]
Itzkowitz et al. [2016] 8 vs 13yrs	-0.68	0.17	197	45	4.8%	-0.68 [-1.01, -0.35]
Itzkowitz et al. [2016] 9 vs 13yrs	-0.91	0.17	203	45	4.8%	-0.91 [-1.24, -0.58]
Nicolini-Panisson et al. [2014] 10-13 vs 14-18yrs	0.71	0.13	129	126	4.9%	0.71 [0.46, 0.96]
Nicolini-Panisson et al. [2014] 6-9 vs 14-18yrs	0.82	0.13	130	126	4.9%	0.82 [0.57, 1.07]
Volkman et al. [2007] 11-12 vs 15-16yrs	0.45	0.28	26	25	4.4%	0.45 [-0.10, 1.00]
Volkman et al. [2007] 7-8 vs 15-16yrs	1.99	0.34	29	25	4.2%	1.99 [1.32, 2.66]
Zaino et al. [2004] 11-12 vs 13-14yrs	0.24	0.56	6	7	3.2%	0.24 [-0.86, 1.34]
Zaino et al. [2004] 8-10 vs 13-14yrs	1.09	0.5	14	7	3.4%	1.09 [0.11, 2.07]
Total (95% CI)			**1810**	**749**	**100.0%**	**0.28 [-0.04, 0.60]**

Heterogeneity: Tau² = 0.52; Chi² = 250.85, df = 22 (P < 0.00001); I² = 91%
Test for overall effect: Z = 1.71 (P = 0.09)

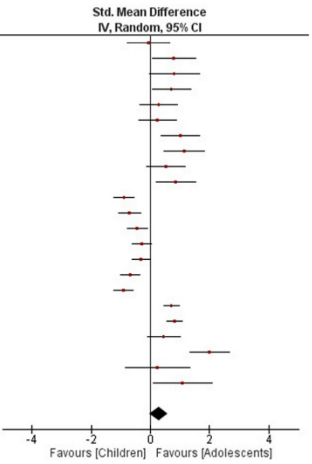

Fig 4. Differences in measures of proactive balance by age (children vs. adolescents). *CI* confidence interval, *df* degrees of freedom, *SE* standard error, *IV* inverse variance.

https://doi.org/10.1371/journal.pone.0214434.g004

Study or Subgroup	Std. Mean Difference	SE	Boys Total	Girls Total	Weight	Std. Mean Difference IV, Random, 95% CI
Arévalo-Mora et al. [2016]	0.09	0.15	90	97	7.5%	0.09 [-0.20, 0.38]
Davies & Rose [2000] Mid-PHV	-0.42	0.45	10	10	1.4%	-0.42 [-1.30, 0.46]
Davies & Rose [2000] Post-PHV	0.42	0.45	10	10	1.4%	0.42 [-0.46, 1.30]
Davies & Rose [2000] Pre-PHV	-0.42	0.45	10	10	1.4%	-0.42 [-1.30, 0.46]
Eguchi & Takada [2014] sSSB 11yrs	0.8	0.46	11	10	1.4%	0.80 [-0.10, 1.70]
Eguchi & Takada [2014] sSSB 9yrs	1.08	0.46	11	11	1.4%	1.08 [0.18, 1.98]
Geldhof et al. [2006] sSSB	0.59	0.21	41	58	5.0%	0.59 [0.18, 1.00]
Holm & Vøllestad [2008] 10yrs	0.06	0.24	29	40	4.1%	0.06 [-0.41, 0.53]
Holm & Vøllestad [2008] 11yrs	0.82	0.27	29	29	3.4%	0.82 [0.29, 1.35]
Holm & Vøllestad [2008] 12yrs	0.37	0.26	28	31	3.7%	0.37 [-0.14, 0.88]
Holm & Vøllestad [2008] 7yrs	0.7	0.29	40	19	3.1%	0.70 [0.13, 1.27]
Holm & Vøllestad [2008] 8yrs	0.07	0.27	29	26	3.4%	0.07 [-0.46, 0.60]
Holm & Vøllestad [2008] 9yrs	0.43	0.25	29	39	3.9%	0.43 [-0.06, 0.92]
Khanna et al. [2015]	0.19	0.21	65	35	5.0%	0.19 [-0.22, 0.60]
Laguna Nieto et al. [2010] sSSB	1.77	0.58	9	9	0.9%	1.77 [0.63, 2.91]
Lee & Lin [2007]	0.25	0.08	365	344	11.9%	0.25 [0.09, 0.41]
Libardoni et al. [2018] 10yrs	0.69	0.46	17	16	1.4%	0.69 [-0.21, 1.59]
Libardoni et al. [2018] 11yrs	-0.14	0.52	16	17	1.1%	-0.14 [-1.16, 0.88]
Libardoni et al. [2018] 12yrs	-0.53	0.46	16	17	1.4%	-0.53 [-1.43, 0.37]
Libardoni et al. [2018] 8yrs	-0.51	0.5	17	16	1.2%	-0.51 [-1.49, 0.47]
Libardoni et al. [2018] 9yrs	0.18	0.39	17	16	1.9%	0.18 [-0.58, 0.94]
McKay et al. [2017] sSSB	0.21	0.16	80	80	7.0%	0.21 [-0.10, 0.52]
Michelotti et al. [2006]	0.37	0.28	28	24	3.3%	0.37 [-0.18, 0.92]
Mickle et al. [2011]	0.53	0.22	37	47	4.7%	0.53 [0.10, 0.96]
Peterson et al. [2006] 10yrs	-0.2	0.45	11	9	1.4%	-0.20 [-1.08, 0.68]
Peterson et al. [2006] 11yrs	0.76	0.5	11	7	1.2%	0.76 [-0.22, 1.74]
Peterson et al. [2006] 12yrs	0.02	0.67	4	5	0.7%	0.02 [-1.29, 1.33]
Peterson et al. [2006] 6yrs	0.97	0.74	5	4	0.6%	0.97 [-0.48, 2.42]
Peterson et al. [2006] 7yrs	0.6	0.4	12	14	1.8%	0.60 [-0.18, 1.38]
Peterson et al. [2006] 8yrs	0.25	0.35	21	14	2.3%	0.25 [-0.44, 0.94]
Peterson et al. [2006] 9yrs	0.38	0.34	16	20	2.4%	0.38 [-0.29, 1.05]
Sheehan & Katz [2012]	0.61	0.26	29	36	3.7%	0.61 [0.10, 1.12]
Sheehan & Katz [2013]	0.49	0.26	33	28	3.7%	0.49 [-0.02, 1.00]
Smith et al. [2012]	0.55	0.42	17	9	1.6%	0.55 [-0.27, 1.37]
Total (95% CI)			**1193**	**1157**	**100.0%**	**0.33 [0.22, 0.44]**

Heterogeneity: $Tau^2 = 0.02$; $Chi^2 = 42.76$, df = 33 (P = 0.12); $I^2 = 23\%$

Test for overall effect: Z = 5.84 (P < 0.00001)

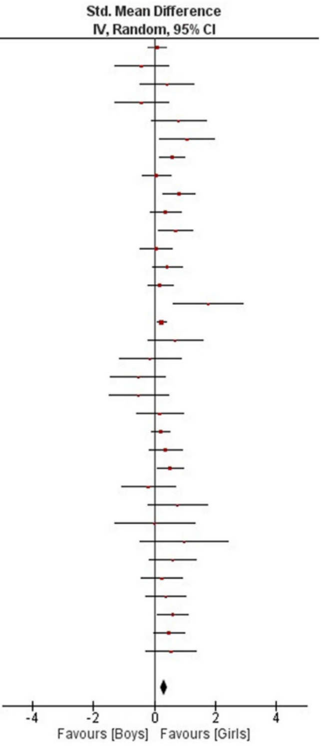

Fig 5. Differences in measures of static steady-state balance by sex (boys vs. girls). *CI* confidence interval, *df* degrees of freedom, *SE* standard error, *IV* inverse variance.

https://doi.org/10.1371/journal.pone.0214434.g005

disagree with studies indicating balance performance to be mature at around ten years of age [1, 74]. We conclude that maturation of balance may not be completed in childhood but possibly continue throughout adolescence in healthy youth.

The age-period between six and eight years of age is considered a transition phase in the development of postural control [15, 75]. At this stage, balance performance sharply increases which has been attributed to better sensory integration and reweighting [76, 77] as well as changes in postural control strategies [11, 12]. Compared to younger peers, it has been shown that children aged six and older perform distinctively better in situations where the equilibrium is perturbed or sensory input is suppressed and conflicting. Furthermore, postural control is gradually organized in a feedforward, anticipatory way and not solely controlled by feedback [78]. Several authors [9, 15, 79] found children at the end of the first decade of life to perform equally well as adults during balancing tasks. They concluded that postural control is mature at this age, although significant developments take place during adolescence also influencing balance performance. Correspondingly, other studies [8, 10, 62] reported further improvements of balance performance throughout adolescence which is in line with our findings.

Study or Subgroup	Std. Mean Difference	SE	Boys Total	Girls Total	Weight	Std. Mean Difference IV, Random, 95% CI
Dufek et al. [2012]	0.17	0.27	33	23	1.9%	0.17 [-0.36, 0.70]
Eguchi & Takada [2014] dSSB 11yrs	0.33	0.43	11	11	0.8%	0.33 [-0.51, 1.17]
Eguchi & Takada [2014] dSSB 9yrs	0.48	0.41	13	12	0.9%	0.48 [-0.32, 1.28]
Geldhof et al. [2006] dSSB	-0.04	0.2	41	58	3.0%	-0.04 [-0.43, 0.35]
Holm et al. [2009] 10yrs	-0.1	0.25	29	39	2.2%	-0.10 [-0.59, 0.39]
Holm et al. [2009] 11yrs	-0.4	0.28	25	28	1.8%	-0.40 [-0.95, 0.15]
Holm et al. [2009] 12yrs	0	0.24	33	37	2.3%	0.00 [-0.47, 0.47]
Holm et al. [2009] 7yrs	0	0.3	36	16	1.6%	0.00 [-0.59, 0.59]
Holm et al. [2009] 8yrs	-0.46	0.29	27	21	1.7%	-0.46 [-1.03, 0.11]
Holm et al. [2009] 9yrs	0.23	0.24	31	38	2.3%	0.23 [-0.24, 0.70]
Müller et al. [2013] 10yrs	-0.1	0.08	315	372	8.1%	-0.10 [-0.26, 0.06]
Müller et al. [2013] 11yrs	-0.06	0.1	200	237	6.9%	-0.06 [-0.26, 0.14]
Müller et al. [2013] 12yrs	-0.09	0.1	180	184	6.9%	-0.09 [-0.29, 0.11]
Müller et al. [2013] 13yrs	-0.01	0.14	98	99	4.9%	-0.01 [-0.28, 0.26]
Müller et al. [2013] 14yrs	-0.19	0.19	52	57	3.3%	-0.19 [-0.56, 0.18]
Müller et al. [2013] 15yrs	0.13	0.23	31	49	2.5%	0.13 [-0.32, 0.58]
Müller et al. [2013] 6yrs	0.11	0.06	455	522	9.4%	0.11 [-0.01, 0.23]
Müller et al. [2013] 7yrs	0.04	0.07	408	426	8.8%	0.04 [-0.10, 0.18]
Müller et al. [2013] 8yrs	-0.08	0.07	385	434	8.8%	-0.08 [-0.22, 0.06]
Müller et al. [2013] 9yrs	-0.13	0.08	320	391	8.1%	-0.13 [-0.29, 0.03]
Thevenon et al. [2015] 10yrs	0.33	0.28	34	20	1.8%	0.33 [-0.22, 0.88]
Thevenon et al. [2015] 11yrs	0.43	0.29	34	20	1.7%	0.43 [-0.14, 1.00]
Thevenon et al. [2015] 12yrs	0.87	0.31	22	25	1.5%	0.87 [0.26, 1.48]
Thevenon et al. [2015] 6yrs	-0.12	0.27	41	20	1.9%	-0.12 [-0.65, 0.41]
Thevenon et al. [2015] 7yrs	0.32	0.29	33	20	1.7%	0.32 [-0.25, 0.89]
Thevenon et al. [2015] 8yrs	-0.35	0.28	34	22	1.8%	-0.35 [-0.90, 0.20]
Thevenon et al. [2015] 9yrs	0.22	0.27	30	27	1.9%	0.22 [-0.31, 0.75]
Öberg et al. [1993] 10-14yrs	-1.43	0.47	12	12	0.7%	-1.43 [-2.35, -0.51]
Öberg et al. [1993] 15-19yrs	-0.7	0.38	15	15	1.0%	-0.70 [-1.44, 0.04]
Total (95% CI)			**2978**	**3235**	**100.0%**	**-0.02 [-0.10, 0.06]**

Heterogeneity: $Tau^2 = 0.01$; $Chi^2 = 47.03$, df = 28 (P = 0.01); $I^2 = 40\%$
Test for overall effect: Z = 0.46 (P = 0.65)

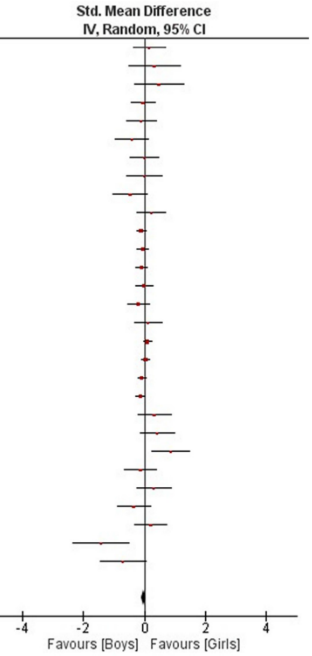

Fig 6. Differences in measures of dynamic steady-state balance by sex (boys vs. girls). *CI* confidence interval, *df* degrees of freedom, *SE* standard error, *IV* inverse variance.

https://doi.org/10.1371/journal.pone.0214434.g006

Increased muscle strength and better attentional capabilities (i.e., to increase focus on a given balance task or challenging situation) may contribute to improved balance performances of adolescents compared to children. For instance, functional measurement tools such as the functional reach test are associated with lower extremity muscular strength in youth [80], potentially giving a slight advantage to older subjects. Moreover, most balance tasks demand high attention of the subject which might be difficult for (younger) children. Walchli et al. [55] for instance limited the test duration of balancing tasks in their study to 15 s in order to minimize bias due to decreased attention of children.

With regard to the results of our meta-analysis, one could conclude that differences in balance performance between children and adolescents might also lead to age-related differences in the trainability of balance in youth. This could be either in favour of children due to highe adaptive reserves or in favour of adolescsents due to their more mature postural control system. There is preliminary evidence that age influences adaptations to anticipated and non-anticipated perturbations in youth after balance training. Walchli et al. [81] compared adaptations to anticipated and non-anticipated perturbations between six- and twelve-year-olds after both age groups received five weeks of child oriented balance training and found younger children to improve similarly in anticipated and non-anticipated perturbations whereas the older children tended to show greater improvements in anticipated perturbations.

Study or Subgroup	Std. Mean Difference	SE	Boys Total	Girls Total	Weight	Std. Mean Difference IV, Random, 95% CI
Butz et al. [2015] 6yrs	0.57	0.46	10	10	1.6%	0.57 [-0.33, 1.47]
Butz et al. [2015] 7yrs	0.26	0.45	10	10	1.6%	0.26 [-0.62, 1.14]
Butz et al. [2015] 8yrs	-0.51	0.46	10	10	1.6%	-0.51 [-1.41, 0.39]
Butz et al. [2015] 9yrs	0.5	0.46	10	10	1.6%	0.50 [-0.40, 1.40]
Butz et al. [2015] 10yrs	-0.19	0.45	10	10	1.6%	-0.19 [-1.07, 0.69]
Butz et al. [2015] 11yrs	-0.51	0.46	10	10	1.6%	-0.51 [-1.41, 0.39]
Butz et al. [2015] 12yrs	0.51	0.46	10	10	1.6%	0.51 [-0.39, 1.41]
Deshmukh et al. [2011] 6yrs	-0.67	0.29	25	25	3.1%	-0.67 [-1.24, -0.10]
Deshmukh et al. [2011] 7yrs	-0.76	0.29	25	25	3.1%	-0.76 [-1.33, -0.19]
Deshmukh et al. [2011] 8yrs	0.06	0.28	25	25	3.2%	0.06 [-0.49, 0.61]
Deshmukh et al. [2011] 9yrs	-0.39	0.29	25	25	3.1%	-0.39 [-0.96, 0.18]
Deshmukh et al. [2011] 10yrs	-0.16	0.28	25	25	3.2%	-0.16 [-0.71, 0.39]
Deshmukh et al. [2011] 11yrs	-0.14	0.28	25	25	3.2%	-0.14 [-0.69, 0.41]
Deshmukh et al. [2011] 12yrs	0.68	0.29	25	25	3.1%	0.68 [0.11, 1.25]
Itzkowitz et al. [2016] 6yrs	-0.06	0.13	124	120	6.3%	-0.06 [-0.31, 0.19]
Itzkowitz et al. [2016] 7yrs	-0.03	0.14	92	129	6.1%	-0.03 [-0.30, 0.24]
Itzkowitz et al. [2016] 8yrs	-0.44	0.14	99	98	6.1%	-0.44 [-0.71, -0.17]
Itzkowitz et al. [2016] 9yrs	-0.58	0.15	73	130	5.8%	-0.58 [-0.87, -0.29]
Itzkowitz et al. [2016] 10yrs	-0.26	0.15	68	112	5.8%	-0.26 [-0.55, 0.03]
Itzkowitz et al. [2016] 11yrs	-0.5	0.21	50	45	4.4%	-0.50 [-0.91, -0.09]
Itzkowitz et al. [2016] 12yrs	-0.05	0.2	36	74	4.6%	-0.05 [-0.44, 0.34]
Itzkowitz et al. [2016] 13yrs	0.14	0.36	10	35	2.3%	0.14 [-0.57, 0.85]
Laguna Nieto et al. [2010] PB	0.41	0.48	9	9	1.4%	0.41 [-0.53, 1.35]
McKay et al. [2017] PB	-0.24	0.16	80	80	5.6%	-0.24 [-0.55, 0.07]
Yuksel et al. [2017] 10yrs	-0.21	0.32	19	21	2.7%	-0.21 [-0.84, 0.42]
Yuksel et al. [2017] 11yrs	-0.15	0.32	17	23	2.7%	-0.15 [-0.78, 0.48]
Yuksel et al. [2017] 12yrs	-0.4	0.32	19	21	2.7%	-0.40 [-1.03, 0.23]
Yuksel et al. [2017] 6yrs	0.48	0.32	20	20	2.7%	0.48 [-0.15, 1.11]
Yuksel et al. [2017] 7yrs	0.42	0.33	15	25	2.6%	0.42 [-0.23, 1.07]
Yuksel et al. [2017] 8yrs	-0.51	0.32	20	20	2.7%	-0.51 [-1.14, 0.12]
Yuksel et al. [2017] 9yrs	0	0.32	18	22	2.7%	0.00 [-0.63, 0.63]
Total (95% CI)			**1014**	**1229**	**100.0%**	**-0.15 [-0.28, -0.03]**

Heterogeneity: Tau² = 0.05; Chi² = 53.43, df = 30 (P = 0.005); I² = 44%
Test for overall effect: Z = 2.42 (P = 0.02)

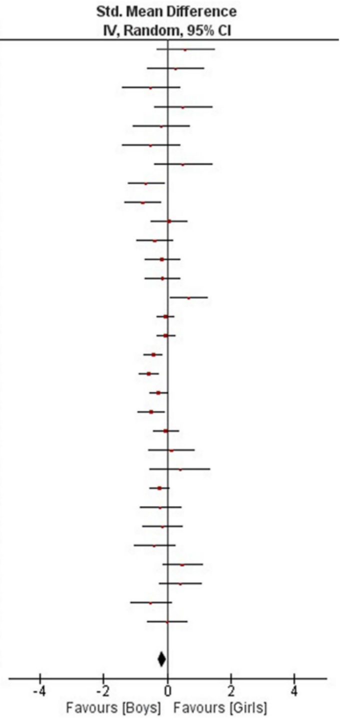

Fig 7. Differences in measures of proactive balance by sex (boys vs. girls). *CI* confidence interval, *df* degrees of freedom, *SE* standard error, *IV* inverse variance.

https://doi.org/10.1371/journal.pone.0214434.g007

Further research investigating the effect of age on balance and its trainability in youth is needed to attain deeper knowledge of the processes underlying the development of postural control and to assist practitioners and clinicians with effective, age-based training regimes. As physical and neural maturation can markedly differ inter-individually, there is a need for large cohort, longitudinal studies on the development of balance performance in youth ideally using MRI as well as balance tests.

Sex differences in balance performance in youth

Analysis of balance performance in youth with regard to a possible gender effect yielded inconsistent results. Being a girl was favorable for measures of static steady-state balance, whereas boys performed better in terms of proactive balance. With respect to dynamic steady-state balance differences between girls and boys seem negligible. Therefore, our second hypothesis that girls exhibit better balance performance than boys is only partially supported by the results.

Maturational differences between girls and boys do not only exist regarding physical, hormonal, and sexual development, but also in terms of central nervous structures [26]. Maturation of the CNS is, amongst others, characterized by a decrease in grey matter volume [14] and increases in white matter volume [14] as well as total cerebellar volume [82]. Similar to

Marshalls' and Tanners' finding that height velocity on average peaks two years earlier in girls than in boys [83, 84], brain developmental studies have shown that brain maturation (e.g., gray matter decrease) occurs in girls prior to boys and is probably also affected by hormonal changes (e. g., sex steroids) accompanying puberty [85]. Consequently, girls reach their peak brain volume earlier than boys [86]. However, these findings must be interpreted carefully as for example regional volumes have to be adjusted for total brain size, which is usually smaller in girls, although not equivalent to any functional differences [13]. Furthermore, earlier brain maturation in girls might give a general advantage to them over boys but not necessarily in terms of balance as many of the described structures are not primarily involved in balance. Lastly, it is difficult to discriminate between effects of development and general sex-effects [86].

From a developmental perspective, it seems reasonable to argue that sex-related differences in balance performance in youth may also be age-dependent. At the beginning of the second decade of life, girls might exhibit better balance performance as they have usually already entered puberty which also leads to advanced maturation of the CNS, while boys typically lag behind in terms of physical and neural development. Contrary, in adolescents aged 15 years for example sex-related differences in balance performance might be smaller as disparities in the level of development are declining or have already been evened out. Therefore, we calculated separate SMD_{bs} for children and adolescents and assumed to find better balance performances of girls in children, but not necessarily in adolescents. However, neither comparison of sex-related balance performance with respect to age groups nor analyses of single SMD_{bs} by age revealed ages or age periods where girls particularly outperform boys or vice versa.

Sex-related differences in balance performance in youth were greatest for measures of static steady-state balance in favor of girls and for measures of proactive balance in favor of boys. Static steady-state balance (e.g., standing on one leg on firm surface) mainly requires the subject to use sensory information and stay concentrated in order to keep the center of mass steadily over the base of support. Contrary, proactive balance as for instance measured with FR requires the subject to move its center of mass to the limits of stability which may also involve other motor skills (e.g., muscular strength). Boys exhibit greater muscular strength than girls in childhood and adolescence and this difference increases with age [26]. Thus, boys may be at an advantage over girls in terms of proactive balance as they can compensate worse balance by greater muscle strength.

Altogether, the inconsistency of our results highlights the need for top-quality studies investigating sex-related differences in balance performance and balance training in youth.

Limitations

A limitation of the present systematic review and meta-analysis is that the analysis of differences in balance performance was limited to the factors age and sex. Maturational processes also affecting the development of balance performance in youth differ in onset and velocity inter-individually, consequently complicating comparisons based on chronological age only. However, only one study [57] in the present meta-analysis reported biological age with subjects being either at the stage of pre-, mid-, or post-peak-height-velocity, leaving us unable to compare balance performances between children and adolescents and/or between girls and boys with respect to biological age, which limits the validity of our analysis. Therefore, future studies on balance performance in youth are advised to also assess biological age of their subjects.

Further, it cannot be ruled out that differences in physical activity between subjects might have influenced our results, although, we corrected for it by excluding data of athletes from our analyses. Thus, further research is needed to investigate differences in balance performance by additional factors like growth, maturation, physical activity, and expertise level.

Only one study [55] reported age- and no study reported sex-specific data for measures of reactive balance performance in youth, while the majority of included studies reported measures of static balance, which may be least important in youth from a functional perspective as daily life activities of children and adolescents (e.g., running, jumping) particularly involve dynamic abilities. Thus, future studies should focus more on dynamic, proactive, and reactive balance performance in boys and girls during childhood and adolescence.

Overall, we observed substantial to considerable heterogeneity between studies investigating age differences in balance performance in youth (I^2 = 59–91%) and trivial to moderate in those on sex differences in balance performance in youth (I^2 = 23–44%), which highlights the need for studies scrutinizing the development of balance performance in youth using the same experimental design in large cohorts covering broad numeric and biological age-ranges.

Conclusions

The present systematic review and meta-analysis characterized and quantified age and sex differences in balance performance in youth. We found better performances in adolescents compared to children for outcomes of static/dynamic steady-state and proactive balance. Therefore, we conclude that balance performance improves from childhood up to late adolescence or early adulthood due to neural maturation and that balance might be differentially trainable in youth. Regarding sex differences, our analyses revealed inconsistent results, highlighting the need for well-designed, large cohort studies on this topic. Because our study was limited to the factors age and sex, further research is needed to determine differences in balance performance by additional factors (e.g., growth, maturation, expertise level).

Supporting information

S1 Table. Quality assessment of included studies.
(XLSX)

S2 Table. PRISMA-checklist–transparent reporting of systematic reviews and meta-analyses.
(DOC)

Author Contributions

Conceptualization: Rainer Kiss, Thomas Muehlbauer.

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4.2 STUDY II – "*Relationships between types of balance in healthy individuals: role of age*"

Aims and Hypotheses: STUDY II aimed to investigate relationships between types of balance and to analyse how these are influenced by age. It was hypothesised that associations between types of balance (i.e., static, dynamic, proactive) would be small in children (7.6 ± 0.6 years), adolescents (14.7 ± 0.5 years), and young adults (22.8 ± 0.8 years). However, it was expected that associations between types of balance would be larger in children and adolescents as compared to young adults. Further, balance performance was expected to be better in older compared to younger age groups.

Results and Conclusions: Except for the relationship between one measure of static balance (i.e., M/L sway) and proactive balance performance in young adults (r = .319, p < .05), associations between measures of static, dynamic, and proactive balance were small-sized and non-significant in children (.302 ≤ r ≤ .245, p > .05), in adolescents (.276 ≤ r ≤ .202, p > .05), and in young adults (.120 ≤ r ≤ .161, p > .05). Comparisons of associations of balance performance between age groups revealed two significant differences. First, and in accordance with the hypothesis, the relationship between dynamic and proactive balance was significantly weaker in young adults (r = .161) compared to adolescents (r = -.276, p = .017) and children (r = -.302, p = .023). Second, and in contrast to the hypothesis, the association between one parameter of static balance (i.e., M/L sway) and proactive balance was significantly larger in young adults (r = .319) compared to adolescents (r = .131, p = .029). Lastly, young adults outperformed adolescents and children in most of the investigated variables. These results indicate that balance is task-specific and that relationships between types of balance performance are only marginally affected by age in the age groups investigated. Different types of balance should therefore be trained and tested individually in children, adolescents, and young adults.

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Relationships between types of balance performance in healthy individuals: Role of age

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ABSTRACT

Background: Balance is considered to be task-specific as indicated by studies reporting only small-sized and non-significant correlations between types of balance (e.g., static, dynamic). However, it remains unclear whether these associations differ by age and the comparability of studies is limited due to methodological inconsistencies.

Research question: Are associations between types of balance performance affected by age in children, adolescents, and young adults?

Methods: Static, dynamic, and proactive balance performance was assessed in 30 children (7.6 ± 0.6 years), 43 adolescents (14.7 ± 0.5 years), and 54 young adults (22.8 ± 2.8 years) using the same standardized balance tests. Pearson's correlation coefficients (r) were calculated for associations between types of balance and statistically compared to detect differences between age groups.

Results: Except for the association between static (i.e., medio-lateral [M/L] sway) and proactive (Y-balance test) balance performance in young adults ($r = .319$, $p < .05$), our analyses revealed small-sized and non-significant associations between measures of static, dynamic, and proactive balance performance in children ($-.302 \le r \le .245$, $p > .05$), adolescents ($-.276 \le r \le .202$, $p > .05$), and young adults ($-.120 \le r \le .161$, $p > .05$). Significant differences between age groups were observed for associations between dynamic and proactive balance, which were lesser in young adults ($r = .161$) compared to adolescents ($r = -.276$, $p = .017$) and children ($r = -.302$, $p = .023$) and for associations between static (i.e., M/L sway) and proactive balance, which were larger in young adults ($r = .319$) compared to adolescents ($r = -.131$, $p = .029$).

Conclusions: Practitioners (e.g., PE teachers) should be aware that associations between types of balance performance are small and hardly affected by age in youth. Therefore, they should be trained and tested individually in children, adolescents, and young adults.

1. Introduction

Sufficient balance performance is an indispensable prerequisite for human beings to successfully cope with activities of daily life (e.g., walking, climbing stairs). According to Shumway-Cook and Woollacott [1], balance can be subdivided into static steady-state (e.g., standing), dynamic steady-state (e.g., walking), proactive (e.g., anticipated slip on a wet floor), and reactive (e.g., tripping over an unseen stair) balance. To ascertain whether these types of balance are associated with each other or represent separate skills, representative measures of the aforementioned balance performances have been assessed and correlated with each other. For example, Muehlbauer et al. [2] investigated associations between static steady-state (i.e., two-legged stance), dynamic steady-state (i.e., 10-m walk test), proactive (i.e., functional reach test [FRT]), and reactive (i.e., perturbed stance) balance performance in healthy children. Except for two comparisons (i.e., center of pressure [CoP] sway in anterior-posterior direction during static and perturbed standing: $r = .458$, $p < .05$; CoP sway in medio-lateral direction during static standing and FRT performance: $r = -.530$, $p < .05$), these researchers [2] found only small-sized ($-.232 \le r \le .431$) and non-significant ($p > .05$) correlations between types of balance performance. Based on these results, it was concluded that balance is a task-specific rather than a general ability in children. Other studies reported similar results in groups of adolescents [3], young [4] and middle-aged [5] adults, as well as in seniors [6].

Balance performance is not stable over the lifespan but increases in

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youth, peaks in young adults, and decreases in seniors [7]. Therefore, associations between types of balance may also be affected by age. For instance, as balance performance still develops in children, different balance tasks may be executed more easily due to a comparatively low level of task automation and a better ability to switch between the execution of different tasks in this age group. In contrast, young adults probably possess a higher level of movement automation which increases the specificity of movement control. Consequently, one could expect that associations between types of balance performance might be larger in children and adolescents as compared to adults. In this regard, Kiss et al. [8] performed a systematic review and meta-analysis by aggregating results and statistically comparing correlations reported in single studies to quantify associations between types of balance in healthy individuals across the lifespan. Supporting the notion, that balance is task-specific rather than a general ability, correlations between types of balance were small (.09 ≤ r ≤ .54), irrespective of the age group considered (i.e., children, adolescents, young, middle-aged, and old adults). Moreover, when statistically comparing correlations between types of balance performance of different age groups, the researchers [8] revealed – contrary to our assumption that associations might be larger in younger individuals – the association between static and dynamic steady-state balance in children (r = .09) to be significantly (p < .01) smaller than that in old adults (r = .31). However, Kiss et al. [8] argued that this age-effect may result from methodological inconsistencies between studies. More specifically, the vast majority of studies included in their analysis used different balance tests, measures, and conditions and was limited to a single age group. For example, both Humphriss et al. [9] as well as Witkowski et al. [10] investigated associations between static and dynamic steady-state balance. However, one study [9] examined associations between heel-to-toe stance on a beam (static balance) and heel-to-toe beam walking (dynamic balance) in children aged ten years, whereas the other [10] analyzed adolescents' (14–15 years) performances in the flamingo (static balance) and the marching (dynamic balance) test. Thus, a direct comparison of associations between types of balance performance of several age groups using identical methods (i.e., testing equipment, test conditions, measures) is still lacking.

Therefore, the main purpose of the present study was to quantify associations between types of balance performance in groups of healthy children, adolescents, and young adults using identical procedures and statistically compare these associations by age group. Based on the assumption that balance is task-specific, we expected to find small-sized correlations between types of balance. We further assumed to observe age-differences for associations between types of balance performance. More precisely, we expected to find larger correlation coefficients in children and adolescents as compared to young adults. A secondary purpose of this study was to compare balance performances of different age groups with our hypothesis being that young adults would show better performances compared to younger individuals (i.e., adolescents, children).

2. Methods

2.1. Subjects

Thirty children (age: 7.6 ± 0.6 years), 43 adolescents (age: 14.7 ± 0.5 years), and 54 young adults (age: 22.8 ± 2.8 years) of both sexes participated in the study. Table 1 shows subjects' characteristics. None of the subjects had prior experience with the tests performed. Moreover, all subjects were healthy and free of any neurological, orthopedic or musculoskeletal impairments. Written informed consent and subject's assent were obtained from all subjects before the start of the study. Additionally, parent's approval was obtained for minors.

Table 1
Study subject's characteristics per age group.

	Children	Adolescents	Young Adults	p-value
n (f/m)	30 (11/19)	43 (16/27)	54 (31/23)	
Age [years]	7.6 ± 0.6	14.7 ± 0.5	22.8 ± 2.8	<.001*
Body height [cm]	131.8 ± 6.2	171.7 ± 8.8	173.5 ± 8.8	<.001+
Body mass [kg]	30.3 ± 6.3	67.0 ± 14.7	73.5 ± 14.5	<.001*
BMI [kg/m²]	17.3 ± 2.6	22.6 ± 4.4	24.2 ± 3.3	<.001+
Maturity offset[1] [years from PHV]	−4.1 ± 0.6	1.8 ± 0.8	7.8 ± 1.9	<.001*

Notes. Values are means ± standard deviations. [1]Maturity offset was calculated by using the formula provided by Moore et al. [12]. *BMI* body mass index, *f* female, *m* male, *PHV* peak height velocity.

* indicates significant differences between all age groups (p < .05).

+ indicates significant differences between young adults/adolescents and children (p < .05).

2.2. Procedures

All tests were performed in gyms by the same skilled assessors. Testing with children and adolescents was carried out during regular physical education lessons at school, while testing with young adults took place during regular university courses. Subjects were divided into small groups and performed all measurements in a randomized order with each group starting with a different test. Before measurement, all subjects received standardized verbal instructions, a visual demonstration of the test and two practice trials to accustom themselves with the respective test. The study was carried out in accordance to the Declaration of Helsinki [11] and was approved by the local ethics committee of the University of Duisburg-Essen.

2.2.1. Anthropometric assessments

Anthropometric measurements included assessments of body height and body mass. Body height was measured to the nearest 0.1 cm using a portable standardised stadiometer (seca 217, Basel, Switzerland) and body mass was assessed to the nearest 0.1 kg with a digital scale (seca 803, Basel, Switzerland). Further, subject's body mass index (BMI) was determined by dividing body mass by the square of body height. Finally, maturity status expressed as years from peak height velocity (PHV) was calculated for all subjects using the formula provided by Moore et al. [12]. Positive values indicate that subjects have passed PHV, whereas negative values indicate that subjects are pre-PHV.

2.2.2. Static steady-state balance performance

Static steady-state balance was assessed during single leg stance on a three-dimensional force platform (AMTI AccuSway, Watertown, USA). Subjects were instructed to stand as stable as possible on their non-dominant leg (i.e., stance leg when kicking a ball) in an upright position for 30 s without shoes. Throughout the trial, subjects had to keep their arms akimbo, flex the knee of the dominant leg to about 90°, and to fixate a cross pinned to the wall approximately one meter opposite to the platform. Data was sampled at 100 Hz and filtered (4th-order Butterworth, 10 Hz cutoff frequency). Center of pressure (CoP) path length (mm), which is the distance travelled by the CoP during the 30-s trial, as well as anterior-posterior (A/P) and medio-lateral (M/L) sway were recorded and used for analysis. Two experimental trials were recorded and the better one was used for analyses.

2.2.3. Dynamic steady-state balance performance

Dynamic steady-state balance was tested using a 10-m walk test. To allow sufficient distance for acceleration and deceleration, subjects initiated and terminated their walk at least one meter before and after the 10-m walkway, respectively. All subjects were instructed to "walk as fast as possible without running" during the trial wearing their own footwear. Using a stopwatch, the time to cover the 10-m distance was recorded to the nearest 0.01 s. Subsequently, gait velocity (m/s) was calculated and used for analysis. Two experimental trials were recorded and the better one was used for analyses.

2.2.4. *Proactive balance performance*

Proactive balance was measured using the lower quarter Y-balance test (YBT) kit (Functional Movement Systems®, Chatham, USA) [13]. Subjects were instructed to reach as far as possible in anterior (AT), posteromedial (PM), and posterolateral (PL) direction with their dominant leg while balancing on the centralized stance platform with their non-dominant leg without shoes. Details on the procedures during this test are described elsewhere [14]. The normalized (i.e., % leg length) maximal reach distance per reach direction and the composite score (CS) were assessed and used for analyses.

2.3. *Statistical analyses*

All data was analyzed for normal distribution using the Shapiro-Wilk test. Subsequently, associations between types of balance within each age group were assessed by calculating Pearson's correlation coefficients (r) and classified as indicating small- ($0 \leq r \leq 0.69$), medium- ($0.70 \leq r \leq 0.89$), or large-sized ($r \geq 0.90$) correlations as proposed by Vincent et al. [15]. Additionally, differences between correlation coefficients by age group (children vs. adolescents vs. young adults) were analysed using the following formula [16]: $z = (z1\text{-}z2)/\sqrt{(1/(n1\text{-}3) + 1/(n2\text{-}3))}$. To detect differences in balance performances between age groups, a 3 (group: young adults, adolescents, children) × 6 (balance parameter: CoP path length, gait velocity, YBT CS, YBT AT, YBT PM, YBT PL) analysis of variance (ANOVA) was performed. If significant group × balance parameter interaction occurred, Bonferroni-adjusted post-hoc tests were carried out. Further, Cohen's d was calculated in order to estimate effect sizes. According to Cohen [17], $d = 0.2$ represent small, $d = 0.5$ represent moderate, and $d = 0.8$ represent large effects. All statistical analyses were carried out using Statistical Package for Social Sciences version 24.0 with the level of significance set at $p < .05$.

3. Results

3.1. *Associations between types of balance performance and the role of age*

Table 2 shows respective r-values for associations between types of balance performance according to age group. Proactive balance performance is represented by the CS as it is considered the most reliable parameter of the YBT in children [18], adolescents [19], and young adults [20]. Overall, our analyses yielded small-sized and non-significant (all $p > .05$) correlations between measures of static steady-state, dynamic steady-state, and proactive balance in children ($-.302 \leq r \leq .245$), in adolescents ($-.276 \leq r \leq .202$), and in young adults ($-.120 \leq r \leq .161$), except for the association between one measure of static steady-state (i.e., M/L sway) and proactive balance which was significant in young adults ($r = .319$, $p < .05$). Moreover, statistically significant differences between age groups were found for the association between one parameter of static steady-state (i.e., M/L sway) and proactive balance as well as for the relationship between dynamic steady-state and proactive balance. With respect to the association between M/L sway and proactive balance, the correlation in young adults ($r = .319$) was significantly larger compared to that of adolescents ($r = -.131$, $z = -2.19$, $p = .029$). Regarding the association between dynamic and proactive balance, the r-value in young adults ($r = .161$) was significantly lesser compared to that of adolescents ($r = -.276$, $z = 2.11$, $p = .017$) and children ($r = -.302$, $z = 1.99$, $p = .023$).

Table 2
Pearson's correlation coefficients (r) for associations between types of balance per age group.

	Children ($n = 30$)			
	Static balance			Proactive balance
	Path length	A/P sway	M/L sway	(i.e., YBT CS)
Dynamic balance (i.e., gait velocity)	−.246	−.141	.233	−.302
Proactive balance (i.e., YBT CS)	.032	.020	.245	–
	Adolescents ($n = 43$)			
	Static balance			Proactive balance
	Path length	A/P sway	M/L sway	(i.e., YBT CS)
Dynamic balance (i.e., gait velocity)	.096	−.070	.202	−.276
Proactive balance (i.e., YBT CS)	.089	.202	−.131	–
	Young Adults ($n = 84$)			
	Static balance			Proactive balance
	Path length	A/P sway	M/L sway	(i.e., YBT CS)
Dynamic balance (i.e., gait velocity)	−.082	.052	−.043	.161[b,c]
Proactive balance (i.e., YBT CS)	−.119	−.120	.319[a,b]	–

Note. A/P anterior-posterior, *CoP* center of pressure, *CS* composite score, *M/L* medio-lateral, *YBT* Y-Balance test.
[a] Indicates significant correlation coefficient ($p < .05$).
[b] Indicates significant difference to adolescents ($p < .05$).
[c] Indicates significant difference to children ($p < .05$).

3.2. *Differences in balance performance between age groups*

Means and standard deviations for balance performances in the different tests according to age group are presented in Table 3.

3.2.1. *Static steady-state balance performance*

Our analysis revealed a significant group effect for CoP path length during single leg stance ($F = 30.1$, $p < .001$). Post-hoc tests showed that young adults ($p < .001$, $d = 2.54$) as well as adolescents ($p < .001$, $d = 2.11$) performed significantly better (i.e., swayed less) than children. However, there was no difference between young adults and adolescents ($p = .090$). Similar results were obtained for A/P ($F = 29.2$, $p < .001$) and M/L ($F = 49.1$, $p < .001$) sway, with post-hoc test indicating significantly better performances of young adults (A/P: $p < .001$, $d = 1.58$; M/L: $p < .001$, $d = 2.05$) and adolescents (A/P: $p < .001$, $d = 1.40$; M/L: $p < .001$, $d = 1.69$) compared to children and no differences between performances of young adults and adolescents (A/P: $p = 1.00$; M/L: $p = 1.00$).

3.2.2. *Dynamic steady-state balance performance*

We detected a significant effect of age group on gait velocity ($F = 19.6$, $p < .001$). Post-hoc analyses indicated faster walking speed of young adults as compared to adolescents ($p < .001$, $d = 1.37$) and children ($p = .003$, $d = 0.72$). No difference regarding gait velocity was observed between adolescents and children ($p = .122$).

3.2.3. *Proactive balance performance*

Concerning performance of the YBT, the analysis indicated significant effects of age group for the CS ($F = 12.1$, $p < .001$), the normalized maximal reach in PM direction ($F = 22.8$, $p < .001$), and the normalized maximal reach in PL direction ($F = 11.2$, $p < .001$). With reference to the CS and PL reach, young adults obtained significantly larger values than adolescents (CS: $p = .026$, $d = 0.64$; PL: $p = .012$, $d = 0.74$) and children

Table 3
Balance performances by age group and results of post-hoc comparisons between age groups.

	Children (CH)	Adolescents (AD)	Young Adults (YA)	Comparisons between age groups p-value (Cohen's d)
Static balance				
CoP path length [mm]	218.9 ± 57.8	127.4 ± 29.5	109.9 ± 31.8	CH – AD: <.001 (2.11) CH – YA: <.001 (2.54) AD – YA: .090 (0.57)
A/P sway [mm]	0.81 ± 0.22	0.54 ± 0.16	0.52 ± 0.15	CH – AD: <.001 (1.40) CH – YA: <.001 (1.58) AD – YA: 1.00 (0.13)
M/L sway [mm]	−0.57 ± 0.14	−0.38 ± 0.09	−0.37 ± 0.07	CH – AD: <.001 (1.69) CH – YA: <.001 (2.05) AD – YA: 1.00 (0.15)
Dynamic balance				
Gait velocity [m/s]	1.5 ± 0.4	1.4 ± 0.3	1.8 ± 0.3	CH – AD: .122 (0.49) CH – YA: .003 (0.72) AD – YA: <.001 (1.37)
Proactive balance				
YBT CS [% LL]	92.0 ± 11.5	96.7 ± 7.3	101.2 ± 6.9	CH – AD: .060 (0.51) CH – YA: <.001 (1.05) AD – YA: .026 (0.64)
YBT AT [% LL]	71.2 ± 8.8	72.2 ± 6.0	71.8 ± 7.3	CH – AD: 1.00 (0.14) CH – YA: 1.00 (0.08) AD – YA: 1.00 (0.05)
YBT PM [% LL]	102.4 ± 14.1	110.6 ± 8.8	117.6 ± 8.0	CH – AD: .002 (0.73) CH – YA: <.001 (1.44) AD – YA: .002 (0.84)
YBT PL [% LL]	102.2 ± 16.8	107.2 ± 9.6	114.2 ± 9.2	CH – AD: .198 (0.39) CH – YA: <.001 (0.97) AD – YA: .012 (0.74)

Note. Values are presented as means ± standard deviations. *AT* anterior reach direction, *A/P* anterior-posterior, *CoP* center of pressure, *CS* composite score, *LL* leg length, *M/L* medio-lateral, *PL* posterolateral reach direction, *PM* posteromedial reach direction, *YBT* Y-Balance test.

(CS: $p < .001$, $d = 1.05$; PL: $p < .001$, $d = 0.97$) whereas no differences were observed between adolescents and children (CS: $p = .060$; PL: $p = .198$). In PM direction, young adults reached farther than adolescents ($p = .002$, $d = 0.84$) and children ($p < .001$, $d = 1.44$). Additionally, adolescents reached farther in PM direction than children ($p = .002$, $d = 0.73$). Lastly, age group did not affect YBT-performance in AT direction ($F = 0.2$, $p = .844$).

4. Discussion

In accordance with our first hypothesis, we observed small-sized and non-significant (all $p > .05$) correlations between measures of static steady-state, dynamic steady-state, and proactive balance in children ($-.302 \leq r \leq .245$), in adolescents ($-.276 \leq r \leq .202$), and in young adults ($-.120 \leq r \leq .161$), except for the association of one parameter of static steady-state balance (i.e., M/L sway) and proactive balance which was significant in young adults ($r = .319$, $p < .05$). This is in accordance with the concept of task-specificity of balance and implies that a person's performance in one specific type of balance (e.g., static steady-state) is not predictive of this person's ability to perform in another type of balance (e.g., proactive). Similar results have been reported by studies in children [2,21], adolescents [3], and young adults [22]. Consequently, if balance performance is tested, examiners should either use test batteries including tests of different types of balance performance or undertake individual measurements for different types of balance. Similarly, common balance training should include manifold exercises challenging all types of balance in order to be most effective. One possible explanation for the predominantly small-sized correlations between types of balance performance relates to the different challenges these tasks pose to the postural control system. For example, during static standing only the center of mass shifts while the base of support is stable, whereas during walking the center of mass and the base of support shift. In this regard, Lajoie et al. [23] have shown that reaction times to an unpredictable auditory stimulus increased during walking as compared to standing in young adults. It was concluded, that walking required higher attentional demands than standing. Further, our results may have been influenced by task difficulty. For instance, the YBT might not be particularly difficult for young adults but represent a major challenge for children as it requires anticipatory postural adjustments. According to Hay and Redon [24], this feedforward organization of postural control develops in youth and undergoes distinct changes in children aged six to eight years, who show a transient overcontrol of posture following self-initiated postural disturbances.

We further hypothesized to find significant differences between associations of types of balance performance of different age groups. However, statistically significant differences were only found for two out of twenty-one comparisons. First, the association between one parameter of static steady-state balance (i.e., M/L sway) and proactive balance in adolescents ($r = -.131$) was significantly smaller compared to young adults ($r = .319$). This is in contrast to our assumption to find larger associations between types of balance performance in children and/or adolescents compared to young adults. However, proactive balance was measured using the CS of the YBT and two (i.e., PM and PL reach) of the three measures included in this parameter require the ability to stabilise the body in M/L direction. Although, this also applies to adolescents, the YBT is a functional test which is also associated with muscular strength, especially of the hip [25]. As muscular strength is still developing in adolescents it may be hypothesized that while they can effectively stabilise their body in M/L direction during a rather simple single-legged stance, their ability to additionally produce enough muscle force during more demanding tasks, such as the YBT, might still be insufficient. Second, dynamic steady-state and proactive balance were significantly more associated in children ($r = -.302$) and adolescents ($r = -.276$) as compared to young adults ($r = .161$). This is in accordance with our hypothesis to find larger associations between types of balance performance in children and adolescents as compared to young adults. With respect to different balance tasks, children and adolescents can be considered as "early in practice" whereas young adults have far more experience with such tasks due to their older age. According to a model proposed by Hikosaka and colleagues [26], the control of a motor task becomes more specific with an increasing level of movement experience. Thus, while children and adolescents may to some degree be able to switch between the execution of different tasks (e.g., static and dynamic steady-state balance), this ability is probably reduced in young adults. However, this finding is in contrast to the results reported in a systematic review with meta-analysis by Kiss et al. [8] who found the association between static and dynamic steady-state balance to be significantly smaller in children compared to old adults (≥ 60 years). Yet, it was argued that this discrepancy might be the result of the different balance tests used in the studies included in their analysis. Although, we investigated young adults only, our results support this assumption as we applied the same balance tests in children, adolescents, and young adults without finding significant differences between associations of static and dynamic steady-state balance in the age groups investigated. Further, the positive correlation in young adults ($r = .161$) means that a faster walking speed is associated with a farther reach in the YBT in this age group and vice versa. Contrary, the negative r-values obtained in children ($r = -.302$) and adolescents ($r = -.276$) suggest that a faster walking speed indicates poorer performance in the YBT and conversely a far reach distance obtained in the YBT is associated with slower walking speed. As the neuromuscular system of children and adolescents is still developing [27] they may have difficulties to adequately master the different challenges of dynamic and proactive balance tasks. For instance, a child may be able to effectively generate balance and strength during walking but struggle to combine balance, strength, and flexibility as needed in the YBT. However, even though we observed a significantly smaller association between dynamic steady-state and proactive balance in young adults as compared to children/adolescents, associations were overall weak and non-significant in all investigated age groups. Thus, the predictive value of a person's performance in one of these tests (e.g., 10-m walk) for the performance in the other test (e.g., YBT) is limited. Consequently, these types of balance should be trained and tested individually.

A second purpose of the present study was to compare balance performances between age groups and in support of our hypothesis, we observed mostly better performances in young adults as compared to adolescents and children. More specifically, young adults outperformed children in seven out of eight and adolescents in four out of eight comparisons of balance performance. Additionally, adolescents showed statistically better performances than children in four out of eight comparisons of balance performance. Lastly, when comparing balance performances between two age groups, the younger group never exhibited better performances than the older age group. This in accordance with other studies reporting balance performance to improve until young adulthood due to the still developing postural control system in children and adolescents [7,28,29]. For example, Cumberworth et al. [29] investigated postural sway in healthy youth aged five to 17 years using the sensory organization test and observed progressive performance increases with age. However, in the present study differences between adolescents and children were only detected regarding static steady-state and partly in proactive balance (i.e., PM reach) and this is in accordance with a systematic review and meta-analysis [30] on age differences in balance performance in youth which reported age to have a large effect on static-steady-state (standardised mean difference [SMD] = 1.20), but only small effects on proxies of dynamic steady-state (SMD = 0.26) and proactive (SMD = 0.28) balance performance. It could therefore be speculated that children possess larger adaptive reserves regarding static steady-state balance than adolescents. In fact, following five weeks of balance training Schedler et al. [31] observed significant improvements in static steady-state balance in children as indicated by decreased postural sway (-16%, $p < .05$) during single-leg stance, whereas the same training elicited slight and non-significant increases (+2%, $p > .05$) of CoP path length in adolescents.

A limitation of the present study relates to the applied tests. We opted for sophisticated biomechanical (i.e., static steady-state balance) as well as more functional physical fitness tests (i.e., 10-m walk test, YBT) providing either high internal or external validity, respectively. Nonetheless, some of these tests may have been too rudimentary to detect differences of associations between types of balance performance.

5. Conclusions

To the best of our knowledge, the present study is the first which investigated and statistically compared associations between types of balance performance between groups of healthy children, adolescents, and young adults using identical balance tests, conditions, and parameters. Our results support the notion that balance is task-specific and different types of balance should therefore be trained and tested separately in these age groups. The influence of age on associations between types of balance performance seems to be small and differences between young adults on the one and children/adolescents on the other side may relate to the still developing postural control system of children and adolescents.

Declaration of Competing Interest

None of the authors has any conflicts of interest.

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4.3 STUDY III – “*Effects of Balance Training on Balance Performance in Youth: Are There Age Differences?*”

Aims and Hypotheses: The aim of STUDY III was to investigate the influence of age on the effectiveness of balance training in youth. Hypotheses were that five weeks of balance training would result in significantly enhanced balance performance in children (7.5 ± 0.5 years) and adolescents (14.7 ± 0.5 years) and that improvements would be significantly larger in adolescents as compared to children.

Results and Conclusions: A significant Test × Group × Age interaction was found for measures of static and dynamic steady-state balance with post hoc tests indicating larger improvements (+16-37%, $.00 \leq p \leq .033$, $0.65 \leq d \leq 2.26$) in children compared to adolescents. No Test × Group × Age interactions were found regarding proactive and reactive balance performance. Thus, the applied training was effective to improve static balance in children and dynamic balance in both age groups, whereas no changes were observed for proactive and reactive balance irrespective of the age group considered. Larger adaptations to balance training in children as compared to adolescents indicate that the immaturity of the postural control system does not seem to inhibit balance training-related improvements. In fact, children seem to benefit from larger adaptive reserves which highlights the particular benefits of balance training in this age group.

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Abstract

Purpose: In youth, cross-sectional studies reported age differences in balance performance that were in favour of adolescents. Thus, trainability of balance performance might be different in children compared to adolescents. The purpose of this study was therefore to compare the effects of balance training (BT) on balance performance between children and adolescents. **Method:** Thirty children (7.5 ± 0.5 years) and 42 adolescents (14.7 ± 0.5 years) participated in this study and were assigned to either a BT-group or a control (CON) group. In both age groups, BT was conducted over five weeks while the CON-groups received their regular physical education lessons. Pre- and post-tests included the assessment of mobility, static steady-state, proactive, and reactive balance. **Results:** Significant Test × Group × Age interactions were found for static steady-state balance (i.e., CoP displacements during single leg stance) and mobility (i.e., 10-m gait velocity). For both measures, post hoc analysis revealed larger improvements (+16-37%, $0.001 \leq p \leq 0.033$, $0.65 \leq d \leq 2.24$) for children compared to adolescents. For proxies of proactive and reactive balance, we could not detect significant Test × Group × Age interactions. **Conclusions:** We conclude that trainability of static steady-state balance and mobility seems to be higher in children than in adolescents indicating larger adaptive reserves in children compared to adolescents. However, there were no age differences in adaptations to BT with respect to proactive and reactive balance.

Key words: Exercise Testing, Learning, Pediatric Exercise

Effects of Balance Training on Balance Performance in Youth: Are There Age Differences?

Good postural control is fundamental for children and adolescents to cope with activities of daily living (e.g., climbing stairs, standing in a moving bus) and to successfully engage in physical activities (e.g., running, hopping, cycling). However, several studies have shown differences in balance performance in youth, with adolescents typically outperforming children. For example, Riach and Hayes (1987) found postural sway during static bipedal stance to decrease with increasing age in children aged two to fourteen years. Similar results were obtained during a dynamic balancing task (Walchli, Ruffieux, Mouthon, Keller, & Taube, 2018), showing that six-year-olds sway significantly more on a swinging platform than eleven- and fifteen-year-olds. Moreover, postural responses after anticipated (Haas, Diener, Bacher, & Dichgans, 1986) as well as non-anticipated perturbations (Shumway-Cook and Woollacott, 1985) reportedly mature with age in youth. Finally, a recent systematic review and meta-analysis (Schedler, Kiss, & Muehlbauer, 2019) investigating differences in balance performance between children and adolescents revealed small (dynamic steady-state/proactive balance) to large (static steady-state balance) effects in favor of adolescents. Age-related differences in balance performance in youth have been attributed to advanced maturation of the postural control system (Woollacott and Shumway-Cook, 1990), neural (Haas, et al., 1986) and physical (Riach and Starkes, 1993) developments, and increased motor experiences (Gouleme, Ezane, Wiener-Vacher, & Bucci, 2014) in adolescents compared to children. These factors may also lead to differences in the trainability of balance between children and adolescents. On the one hand, trainability of balance might be higher in adolescents compared to children due to their almost mature postural control system, which might be a prerequisite for pronounced training adaptations. On the other hand, children might be better trainable due to their lower level of performance leaving them with higher adaptive resources compared to adolescents.

So far, there have only been a few original studies on age-dependent effects of balance training (BT) in youth. Walchli et al. (2018b) examined adaptations to five weeks of child-oriented BT in children and adolescents aged six to fifteen years. Although, no effects were observed with respect to static steady-state balance (e.g., center of pressure [CoP] sway during tandem stance), BT was effective to promote dynamic balance (e.g., CoP sway during single leg stance on a spinning top) in all age groups, with the youngest children showing the largest improvements. In another study (Walchli, Keller, Ruffieux, Mouthon, & Taube, 2018), these authors examined age-dependent adaptations of BT to anticipated and non-anticipated perturbations in six- versus twelve-year-olds. In both age groups, BT resulted in improved proactive/reactive postural stability without significant differences between six- and twelve-year-olds. Finally, Gebel et al. (2018) conducted a systematic review and meta-analysis on the effectiveness of BT in youth. Their analysis revealed BT to be equally effective to promote static/dynamic balance in children and adolescents, although the observed effect size was higher for children (SMD = 1.28) compared to adolescents (SMD = 0.84). However, these authors (Gebel, et al., 2018) emphasized the preliminary character of their findings due to high heterogeneity between studies and insufficient methodological quality of the majority of included studies. Even though, the aforementioned studies added significantly to age-effects of BT in youth, their individual evidence is limited to certain aspects of balance (e.g., proactive/reactive balance), while it remains unclear if the observed effects also apply for other aspects of balance control (e.g., static/dynamic steady-state balance) in a particular sample.

Therefore, the objective of this study was to systematically investigate the effects of BT on measures of mobility, static steady-state, proactive, and reactive balance performance in children compared to adolescents. We expected that BT will result in significant improvements in balance performance in children as well as in adolescents. We further hypothesized, that the observed BT-related improvements will be greater in children compared to adolescents.

Method

Participants

Thirty children (14 boys, 16 girls, 7.5 ± 0.5 years) from two primary school classes and 42 adolescents (26 boys, 16 girls, 14.7 ± 0.5 years) from two secondary school classes participated in this study after experimental procedures were explained. Because the classes were rigid in their composition, randomization was only possible on a class but not on an individual level. Consequently, each class was randomly defined to be either a BT-group (children: 3 boys, 8 girls; adolescents: 17 boys, 8 girls) or a control (CON) group (children: 11 boys, 8 girls; adolescents: 9 boys, 8 girls). Table 1 shows participants' characteristics for each group. No significant differences in anthropometric data (i.e., body height, body mass) were found between intervention and control groups in children and adolescents, respectively. Additionally, we checked for differences in maturity status using sex-specific equations introduced by Moore et al. (2015). Participants from the children's group were classified as being pre-peak height velocity (PHV) without significant differences between children from the BT- and the CON-group ($p = 0.448$). Similarly, maturity status did not differ between the adolescent's BT- and CON-group ($p = 0.075$). However, there was a significant difference in maturity status between the pre-PHV children, and the post-PHV adolescents ($p < 0.001$). None of the students had any history of musculoskeletal, neurological, or orthopedic disorder that might have affected their ability to execute the BT program, the physical education (P.E.) lessons, and/or the balance tests. Participants' assent and parents' written informed consent was obtained before the start of the study. The local Human Ethics Committee approved the study protocol (code: TM_29.11.2018).

Training Protocols

Each group exercised separately for five weeks (2-3 times per week with a total of 135 minutes per week) during regular P.E. lessons at the school gym, supervised by their respective P.E. teacher and a graduate student. Each training session started with a 10-minute warm-up and finished with a 5-minute cool down program.

The BT-groups performed a BT program that was based on recommendations provided by Granacher et al. (2011) and is summarized in Table 2. Each training session included 5-8 exercises for the training of mobility, static steady-state, proactive, and reactive balance. Three trials per exercise (each trial lasted 30 s) were conducted. The rest period between trials and exercises was 30 s and 1 min, respectively. Training progression was achieved by a gradual manipulation of the stance and walking conditions and by removing the visual input (Table 2). Further, the number of balance exercises was gradually increased.

Instead of the BT program, the students in the CON-groups underwent their regular P.E. lessons using the same training volume (i.e. 5 weeks with a total of 135 min per week). The regular P.E. lessons consisted of ball games (i.e. soccer and basketball).

Testing Procedure

All balance tests were conducted in gyms by the same assessors (graduated sport scientists) during pre- and post-tests. Examiners were trained and achieved competence for the respective balance test in a study course. In addition, they were blinded to group allocation. The students received standardized verbal instructions regarding the test procedure. Subsequently, the following schedule of testing started: (1) measurement of anthropometric data (i.e. body height, body mass, leg length); (2) a standardized 10-min warm up program consisting of static/dynamic steady-state, proactive, and reactive balance exercises; (3) assessment of mobility, static steady-state, proactive, and reactive balance. Balance exercises were performed during warm-up to prepare participants physiologically and psychologically for the following tests. Even though exercises were unspecific and unlike the tests it may have led to better performances during measurements. Although, usually several trials are collected and then averaged, participants performed 1-2 practice trials followed by one data-collection trial, if not otherwise stated. This rather uncommon approach was adopted as all data collecting took place during regular P.E. lessons lasting approximately 60 minutes only. However, if participants failed to perform a test correctly, trials were repeated until at least one valid trial was accomplished. All test procedures were identical during pre- and post-tests.

Testing Material

Static steady-state balance was tested using the single leg stance (Zumbrunn, MacWilliams, & Johnson, 2011) while standing on a three-dimensional force plate (AMTI AccuSway, Watertown, USA). We asked students to stand as stable as possible on their non-dominant leg (determined per self-report) in an upright position for 30 s without shoes, arms akimbo, gaze fixated on a cross located on a wall approximately one meter opposite to the platform, and eyes opened. This test showed high reliability in school-aged children indicated by spearman's rank correlation coefficients of 0.91-1.00 (Atwater, Crowe, Deitz, & Richardson, 1990). Data was sampled at 100 Hz and processed using a fourth-order Butterworth filter with a cut-off frequency of 10 Hz. CoP displacement was calculated as the resultant travelled distance of the x- and y-coordinates of the CoP using the following formula:

$$CoP_{Path\ length} = \sum_{i=2}^{n} \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}$$

Mobility was assessed using the 10-m walk test (Dusing and Thorpe, 2007). Students walked with their own footwear, initiating and terminating the walk a minimum of 1 m before and after the 10-m walking distance to allow sufficient distance to accelerate and decelerate. We instructed participants to "walk as fast as possible without running". The time needed to cover the 10-m distance was recorded with a stopwatch to the nearest 0.01 s. Afterwards, gait velocity (m/s) was calculated and used for further analysis.

Proactive balance was measured using the Lower Quarter Y Balance Test (LQ-YBT) which shows "moderate-to-good" to "excellent" reliability in school-aged youth with ICCs ranging from 0.40 to 0.96 (Calatayud, Borreani, Colado, Martin, & Flandez, 2014; Schwiertz, Brueckner, Schedler, Kiss, & Muehlbauer, 2019). Briefly, the Y Balance Test Kit (Functional Movement Systems, Chatham, USA) was placed on the gym floor and each student had to stand barefoot with the non-dominant leg on the centralized stance platform and to move the reach indicator with the dominant leg as far as possible in in the anterior (AT), posteromedial (PM), and posterolateral (PL) direction. Each student performed three practice trials followed by three data-collection trials. Trials were discarded if participants (i) lost their balance, (ii) lifted the stance leg from the centralized stance platform, (iii) stepped on top of the reach indicator for support, or (iv) kicked the reach indicator. Maximal reach distance (cm) for each of the three reach directions was assessed to the nearest 0.5 cm. Afterwards, the normalized (% leg length) maximal reach distance per reach direction was calculated and used for further analysis.

Reactive balance was tested using the Push and Release Test (PRT) (Jacobs, Horak, Van Tran, & Nutt, 2006), which has actually been developed for people with balance deficits (e.g.,, Parkinson's disease). However, due to our experimental setup we predominantly opted for field-based tests and to the best of our knowledge there is no other field-based test to assess reactive balance so far. The students were asked to stand without shoes and to push backward against the palms of the examiner's hands that were placed on the participant's scapulae. Afterwards, we asked the students to move their shoulders and hips just behind their heels. Thereafter, the examiner suddenly removed her/his hands, requiring the participant to take at least one step backwards to regain balance. The step number and the quality of the recovery was judged as follows: 0 point = 1 step, 1 point = 2–3 small steps with independent recovery, 2 points = $\geq$ 4 steps with independent recovery, 3 points = multiple steps with assistance for recovery, 4 points = fall or unable to stand without assistance.

Intraclass correlation coefficients (ICC) were calculated for all balance measures on the basis of ICC3,*k* (i.e., two-way mixed-effects, consistency, multiple raters/measurements model) using pre- and post-test data of the CON-groups and proved to be excellent for all measures except PRT which showed fair to good test-retest reliability (Table 3).

Statistical Analyses

An a priori power analysis using G * Power (Faul, Erdfelder, Lang, & Buchner, 2007) with the following input parameters was performed to obtain medium-sized test × group × age interaction effects: effect size ($f = 0.25$), type I error ($\alpha = 0.05$), type II error ($1-\beta = 0.95$), number of groups ($n = 4$), number of measurements ($n = 2$), correlation between measurements ($r = 0.60$). Additionally, a dropout rate of 20% was considered. The use of a medium effect size was based on a similar study conducted by Walchli et al. (2018b) who compared the effects of BT on measures of static/dynamic steady-state balance between children and adolescents. Our analysis revealed a total sample size of 72 participants.

Normal distribution of data was examined using the Shapiro-Wilk test. Descriptive statistics for interval scaled data (i.e. measures of mobility, static steady-state balance, and proactive balance) were presented as group means ± standard deviations (SD). For ordinal scaled data (i.e. proxies of reactive balance), the median and interquartile range was calculated as descriptive data. Performance differences in the pre-test values between BT- and CON-groups per age group were assessed using either the independent sample t-test for interval scaled data or the non-parametric Mann-Whitney-U test for ordinal scaled data. Variables of static mobility, steady-state balance, and proactive balance were analyzed in separate 2 (test: pre-test, post-test) × 2 (group: BT, CON) × 2 (age: children, adolescents) ANOVA with repeated measures on test. Pre-test performance values were included as covariates to adjust for baseline differences between groups. For measures of reactive balance, differences between post-test minus pre-test values were calculated and statistically compared (BT-group versus CON-group) per age group using the Mann-Whitney-U test. Additionally, Cohen's *d* (Cohen, 1988) was calculated for the interval scaled data as an effect size measure. Finally, the $p_{a,b}$-value (Grissom and Kim, 2012) was calculated as an effect size measure for ordinal scaled data by dividing the Mann-Whitney-U statistics by the product of the two sample sizes (i.e., BT children × CON children, BT adolescents × CON adolescents). All analyses were carried out using the Statistical Package for Social Sciences (SPSS) version 24.0 and significance level was set at $p < 0.05$.

Results

All participants received treatment (i.e. BT lessons) or control (i.e. regular P.E. lessons) conditions as allocated. None of the participants reported any test- or training-related injury. Seven children (BT-group: n = 5, CON-group: n = 2) and three adolescents (BT-group: n = 1, CON-group: n = 2) did not perform the post-test due to health reasons not attributable to treatments. The attendance rates during training sessions amounted to 98% (BT-group) and 95% (CON-group) in children and to 97% (BT-group) and 94% (CON-group) in adolescents. Table 4 displays descriptive statistics for all analyzed variables. In children and in adolescents, there were no statistically significant differences in the pre-test values between the BT- and CON-groups. Finally, Table 5 displays the ANOVA outcomes including all three- and two-way interactions as well as results of the analysis of a potential test × sex interaction. In depth results are presented separately for each measure in the following paragraphs.

Static Steady-State Balance Performance

We found a significant Test × Group × Age interaction for the CoP displacements during single leg stance ($F_{(1, 56)} = 7.690$, $p = .008$, $d = 0.74$) (Figure 1). Post hoc analysis revealed significant improvements for children in the BT-group illustrated by a reduced CoP path length (-16%, $p = .033$, $d = 0.65$) but not for adolescents in the BT-group who exhibited slightly increased CoP displacements (+2%, $p = .605$, $d = 0.05$) during single leg stance.

Mobility

We detected a significant Test × Group × Age interaction for 10-m gait velocity ($F_{(1, 67)} = 10.358$, $p = .002$, $d = 0.78$) (Figure 2). Post hoc analysis revealed significant improvements in both BT-groups that were larger in children (+37%, $p < .001$, $d = 2.24$) compared to adolescents (+12%, $p < .001$, $d = 0.88$).

Proactive Balance Performance

Only for the PL reach direction, we found a significant Test × Group interaction ($F_{(1, 67)} = 7.986$, $p = .006$, $d = 0.69$). Post hoc analysis revealed significant improvements for the BT-groups (+4.7%, $p = .015$, $d = 0.36$) but not for the CON-groups (-1.7%, $p = .251$, $d = 0.05$). However, we did not detect any significant Test × Group × Age interactions.

Reactive Balance Performance

Irrespective of age group, we did not find significant differences for the pre- to post-test changes (i.e., delta values) in the PRT performance between the BT- and CON-groups in children ($p = .696$, $p_{a.b} = 0.46$) and adolescents ($p = .102$, $p_{a.b} = 0.36$).

Discussion

In the present study, we compared the effects of BT on balance performance of children versus adolescents. Our main findings can be summarized as follows: (i) five weeks of BT proved to be safe (i.e. no training-related injury) and feasible with high attendance rates (98% in children and 97% in adolescents); (ii) in children and in adolescents, BT resulted in significant improvements in measures of static steady-state balance (i.e. CoP displacements during single leg stance) and mobility (i.e. 10-m gait velocity) which were significantly larger in children compared to adolescents; (iii) irrespective of age group, BT failed to significantly improve performances in the applied measures of proactive and reactive balance.

Effects of BT on Balance Performance

We partially confirmed our first hypothesis that BT will result in significant improvements in balance performance in children as well as in adolescents. Significant improvements were found for measures of static steady-state balance and mobility but not for proxies of proactive (except for the PL reach direction in the LQ-YBT) and reactive balance. For children, the present findings disagree with those of Granacher et al. (2011) who did not find significant effects of BT on balance performance in six-year-old children. However, these authors measured dynamic steady-state balance (i.e., CoP-displacement during two-legged stance on a swinging platform) whereas we measured mobility (i.e., gait speed) which limits the comparability of the results. Nonetheless, Granacher et al. (2011) attributed their findings to the immaturity of the postural control system in six-year-olds as major developments (e.g., ability to suppress inappropriate sensory input) reportedly only emerge by the age of seven (Berger, Quintern, & Dietz, 1985; Forssberg and Nashner, 1982; Foudriat, Di Fabio, & Anderson, 1993). As we examined seven-year-olds, children in our study may have taken this milestone in the development of postural control, thus showing larger adaptations to BT. Moreover, although BT was similar in terms of weekly training time and training content in both studies, we conducted five weeks of BT whereas children trained for four weeks in the study of Granacher et al. (2011). It may therefore be speculated that BT in young children has to be conducted for a minimum of five weeks until improvements in dynamic steady-state balance become evident.

Concerning adolescents, our results are in line with those of Granacher et al. (2010) who reported significant reductions in postural sway in adolescents after four weeks of BT. However, their findings are limited to static steady-state balance (i.e. CoP sway during single leg stance) as no data on measures of dynamic steady-state, proactive, or reactive balance were collected. Recently, Gebel et al. (2018) conducted a systematic review and meta-analysis on the effects of BT in youth analyzing data of 17 different controlled trials. Similar to our results, these authors (Gebel, et al., 2018) found a moderate effect in terms of static balance and a large effect regarding dynamic balance illustrating the effectiveness of BT in youth, irrespective of age, sex, training status, setting, or testing method. However, in this study (Gebel, et al., 2018) dynamic balance comprised data of dynamic steady-state, proactive, and reactive balance measures, whereas we analyzed mobility instead of dynamic steady-state balance. Additionally, separate analysis of proactive and reactive balance in our study did not reveal BT-induced improvements for these measures (except for the PL reach direction in the LQ-YBT) in children and adolescents. However, the PRT was originally developed to assess reactive balance in Parkinson's disease patients and may therefore be less sensitive in people with sufficient balance (e.g., healthy youth) (Jacobs, et al., 2006). Consequently, the PRT probably was not sensitive enough to detect BT-induced improvements as most participants performed well at baseline already and/or produces a learning effect as CON-groups showed improvements comparable or even larger than BT-groups. To prevent such effects, researchers should use other tests (e.g., perturbed stance on a force platform) and/or more sophisticated instrumentation (e.g., inertial sensors) when assessing reactive balance in youth > 6 years. However, due to the experimental setup (e.g., testing in school gyms during regular P.E. lessons) and limited equipment we opted for easy to administer functional measures in our study.

Overall, BT seems to be a feasible and effective means to promote static steady-state balance and mobility in PE lessons in children as well as in adolescents. However, the conducted training regime did not have beneficial effects on proactive balance and no conclusions can be drawn regarding reactive balance control.

Age-Related Effects of BT on Balance Performance

In our second hypothesis we expected BT-related improvements to be significantly larger in children compared to adolescents. Consistent with this assumption, we found significantly larger improvements for measures of static steady-state balance and mobility in children than in adolescents. However, no age-related effects of BT were observed for proxies of proactive and reactive balance. Therefore, our second hypothesis is only partially supported by our results. These findings are in line with two former studies of Walchli and colleagues (2018a; 2018b). Investigating the effects of five weeks child-oriented BT on static and dynamic steady-state balance in six-, eleven-, and fourteen-year-olds, Walchli et al. (2018b) found BT-induced improvements to be significantly larger in six-year-olds compared to eleven- and fourteen-year-olds. Higher trainability of children compared to adolescents was attributed to larger adaptive reserves in children, as they performed significantly worse at baseline. However, these findings were limited to dynamic balancing tasks performed in single leg stance while no BT-related improvements were reported for easier static/dynamic balancing tasks performed in two-legged stance. To avoid such ceiling effects, we assessed static balance under more challenging conditions (e.g., single leg stance) and thus observed enhanced static steady-state balance after BT in children as well as adolescents, but with children showing larger improvements than adolescents.

To examine age-dependent adaptations to BT with respect to proactive and reactive balance, Walchli et al. (2018a) compared balance performances of six- and twelve-year-olds on a free swinging platform after anticipated and non-anticipated externally induced perturbations. Although, there were differences in training adaptations between children and adolescents depending on the test condition (anticipated vs. non-anticipated perturbation), no significant age differences in terms of the overall effect of BT were found, which is in line with our findings. However, in contrast to this study we did not find improvements in proactive/reactive balance at all which may be attributed to differences in the applied tests.

Larger adaptations to BT in children compared to adolescents may be attributed to larger adaptive reserves in children. The somatosensory and vestibular system slowly mature throughout childhood and even into adolescence, especially with respect to vestibular function (Hirabayashi and Iwasaki, 1995; Peterson, Christou, & Rosengren, 2006), leading to greater reserves of these systems to adapt to BT in children. Consequently, the immaturity of the postural control system in young children does not seem to inhibit adaptations to BT and might even lead to larger improvements in balance performance after BT in children compared to adolescents. Therefore, it seems reasonable to include BT in P.E. lessons of young children attending elementary school in order to promote static steady-state balance and mobility. However, children do not seem to possess any advantages over adolescents concerning the effectiveness of BT with respect to proactive balance and no conclusions can be drawn regarding reactive balance as the administered test (i.e., PRT) was probably not sensitive enough to detect changes.

Limitations of the present study particularly relate to the school setting. The intervention period was restricted to five weeks, although evidence suggests that BT should be carried out for eight weeks in order to be most effective (Gebel, et al., 2018). Moreover, randomization occurred on class-level only and the use of predominately field-based tests may have biased our results as for instance the PRT has been developed for an entirely different population. As all testing was performed during regular P.E. classes, we were forced to limit testing to one valid trial for most measures, which might have affected reliability of our data. Additionally, the findings of the present study are limited to the examined age groups (i.e. seven- and fourteen-year-olds). Therefore, we cannot comment on age-related adaptations to BT in other groups of children (e.g., >8 years) and adolescents (e.g., >15 years). Furthermore, the underlying mechanisms of BT-induced improvements in balance performance in youth remain unclear as our methodical approach was limited to balance performance measures. Finally, the influence of different BT modalities (i.e. training frequency, duration, intensity) on balance performance in youth cannot be appraised by the results of the present study and should be addressed in future research.

Conclusions

The present study systematically investigated the effects of BT on measures of static steady-state balance, mobility, proactive, and reactive balance performance in children compared to adolescents. In both age groups, the applied BT program resulted in significant improvements on proxies of static steady-state balance and mobility that were larger in children as in adolescents. Based on that, we suggest that trainability of static steady-state balance and mobility is higher in children than in adolescents. A larger adaptive reserve in children might explain this finding. Further research on age-dependent adaptations to BT regarding proactive and reactive balance in youth is mandatory.

What Does This Article Add?

It has been shown that in youth balance performance is affected by age. Thus, age might also affect balance trainability in youth. Previous studies focused on training effects on particular balance components (e.g., proactive balance) in various age groups. This study examined the effectiveness of a five week BT-program during regular P.E. classes on performance of three components of balance (i.e., static steady-state, proactive, reactive) and mobility (i.e., gait speed) within one sample. Although, children as well as adolescents improved their static steady-state balance performance and mobility, children benefitted more from BT than their older counterparts. Consequently, the immaturity of the postural control system in children does not seem to hamper BT-induced adaptations. Our findings might be explained by larger adaptive reserves in children and suggest that these may be utilized by P.E. teachers or sport coaches to enhance balance performance already at young ages. However, the administered training was not efficient to improve reactive and proactive balance performance in neither age group indicating that either the training was ineffective or that the applied tests were not sensitive enough to detect changes.

Disclosure Statement

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Table 1.

Characteristics of the study participants

	Children (*n*=30)		Adolescents (*n*=42)	
	BT-group (*n*=11)	CON-group (*n*=19)	BT-group (*n*=25)	CON-group (*n*=17)
Age (years)	7.4 ± 0.3	7.7 ± 0.6	14.7 ± 0.5	14.7 ± 0.5
Sex (f/m)	8/3	8/11	8/17	8/9
Body height (cm)	129.2 ± 7.1	132.0 ± 5.9	170.7 ± 8.5	172.7 ± 9.8
Body mass (kg)	28.4 ± 7.7	31.0 ± 5.1	68.4 ± 14.8	67.5 ± 15.9
Maturity offset[1] (Years from PHV)	-4.17 ± 0.55	-4.02 ± 0.65	1.65 ± 0.74	2.05 ± 0.70

Note: Values are means ± standard deviations. [1]Maturity offset was calculated by using the formula provided by Moore et al. (2015). There were no significant differences between groups per age category. BT-group = balance training group, CON = control group (i.e., regular P.E. lessons); f = female; m = male; PHV = peak height velocity.

Table 2.

Protocol of the balance training program

Balance exercises	-static steady-state balance (i.e. standing exercises) -dynamic steady-state balance (i.e. walking exercises) -proactive balance (i.e. weight shifting while standing) -reactive balance (i.e. perturbed standing)
Training volume	-5 weeks with 135 minutes per week -each session included 5-8 balance exercises that required static/dynamic steady-state, proactive, and reactive balance performances -3 trials per exercise (each trial lasted 30 s) - 30 s and 1 minute of rest between trials and exercises, respectively
Training progression	-use of unstable training devices (i.e. soft mats, ankle disks, balance pads, foam cushions, ARTZT® vitality Wobblesmart) -reduction of the base of support while standing (i.e. from bipedal stance over semi-tandem and tandem stance to single leg stance) -use of different walking conditions (i.e. from normal gait over narrow and overlapping gait to tandem gait), speeds (i.e. slow, habitual, fast), and directions (i.e. forward, backward, sideward) -remove of visual information (i.e. training with eyes closed) -increase of exercise number (i.e. from 5 to 8 exercises)

Table 3.

Intraclass correlation coefficients (ICC) for all balance measures

Variable (Measure)	ICC
CoP Path (static steady-state balance)	0.89
Gait velocity (mobility)	0.77
Y Balance Test AT (proactive balance)	0.91
Y Balance Test PM (proactive balance)	0.96
Y Balance Test PL (proactive balance)	0.96
PRT (reactive balance)	0.43

Note. AT = anterior reach direction; CoP = center of pressure; PL = posterolateral reach direction; PM = posteromedial reach direction; PRT = push and release test

Table 4.

Age-related effects of the balance training program on measures of mobility, static steady-state, proactive, and reactive balance in youth

	Children (n=30)				Adolescents (n=42)			
	BT-group (n=11)		CON-group (n=19)		BT-group (n=25)		CON-group (n=17)	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Static balance								
CoP (cm)	208.8 ± 50.7	174.9 ± 52.8	187.2 ± 59.5	186.8 ± 44.7	121.2 ± 29.4	124.0 ± 23.3	114.6 ± 26.9	100.9 ± 26.1
Mobility								
Gait velocity (m/s)	1.36 ± 0.22	1.87 ± 0.27	1.59 ± 0.38	1.69 ± 0.31	1.35 ± 0.15	1.51 ± 0.19	1.41 ± 0.23	1.50 ± 0.19
Proactive balance								
AT (%)	73.1 ± 7.4	73.6 ± 6.0	67.5 ± 8.6	70.5 ± 6.3	71.6 ± 5.7	72.3 ± 8.5	78.4 ± 26.0	79.2 ± 28.5
PM (%)	106.6 ± 14.7	109.5 ± 13.1	97.3 ± 11.6	99.9 ± 12.6	111.0 ± 9.1	116.3 ± 12.9	120.0 ± 45.0	119.2 ± 43.2
PL (%)	104.3 ± 16.3	108.5 ± 13.9	100.5 ± 17.6	98.6 ± 11.1	107.8 ± 10.2	112.9 ± 15.9	116.4 ± 48.0	114.8 ± 48.0
Reactive balance								
PRT (pt)	2.0 (1.5-3-5)	2.0 (1.5-3.0)	2.0 (1.0-2.0)	1.0 (1.0-2.0)	2.0 (1.0-2.0)	1.0 (1.0-2.0)	2.0 (2.0-2.0)	1.0 (1.0-2.0)

Note. AT = anterior reach direction; BT-group = balance training group, CON-group = control group (i.e. regular P.E. lessons); CoP = center of pressure; PRT = push and release test; PL = posterolateral reach direction; PM = posteromedial reach direction.

Table 5.

Analysis of covariance outcomes (adjusted for sex) for the measures of mobility, static steady-state balance, proactive balance, and reactive balance

	Test × Sex		*Test × Group*		*Test × Age*		*Test × Group × Age*	
	p-value	*d*-value	*p*-value	*d*-value	*p*-value	*d*-value	*p*-value	*d*-value
Static balance								
CoP (cm)	.197	.35	.393	.23	.202	.35	**.008**	**.74**
Mobility								
Gait velocity (m/s)	.832	.06	**<.001**	**1.02**	**.002**	**.76**	**.002**	**.78**
Proactive balance								
AT (%)	.557	.14	.458	.18	.600	.13	.577	.14
PM (%)	.768	.06	.231	.29	.843	.06	.256	.28
PL (%)	.108	.40	**.006**	**.69**	.952	.06	.955	.05
Reactive balance								
PRT (pt)			.696[a]	.46[a]				
			.102[b]	.36[b]				

Note. Significant interaction effects are displayed in bold. [a] p-values and effect sizes for comparison between children's BT- and CON-group; [b] p-values and effect sizes for comparison between adolescent's BT- and CON-group; AT = anterior reach direction; BT-group = balance training group, CON-group = control group (i.e. regular P.E. lessons); CoP = center of pressure; PRT = push and release test; PL = posterolateral reach direction; PM = posteromedial reach direction

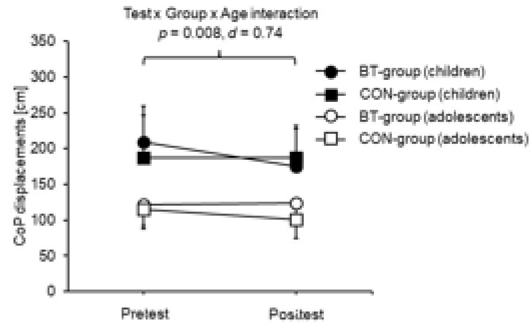

Figure 1. Performance changes (mean ± standard deviation) during the intervention period in static steady-state balance (i.e., center of pressure [CoP] displacement during single leg stance) for the balance training (BT) compared to the control (CON) groups by age.

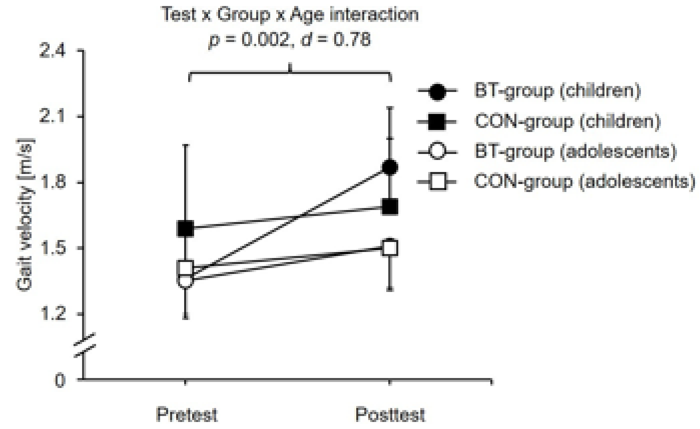

Figure 2. Performance changes (mean ± standard deviation) during the intervention period in dynamic steady-state balance (i.e., 10-m gait velocity) for the balance training (BT) compared to the control (CON) groups by age.

4.4 STUDY IV – "*Effect of practice on learning to maintain balance under dynamic conditions in children: are there sex differences?*"

Aims and Hypotheses: STUDY IV aimed to investigate the influence of sex in children learning a new dynamic balance task (i.e., balance on a stabilometer). Hypotheses were that practicing a novel dynamic balance task on two consecutive days would lead to short-term adaptations resulting in performance increases in the trained task in primary school-aged children (8.5 ± 0.5 years) and that these improvements would be larger in girls compared to boys. Additionally, it was expected that long-term effects as proven in a delayed retention and an automation test on the third day would be evident in both sexes with better performances of girls compared to boys.

Results and Conclusions: During practicing performances significantly improved with respective trials (p = .003, d = 0.70) and from day 1 to day 2 (p = .019, d = 0.92) as indicated by decreases in RMSE values in girls and boys. However, the main effect of sex just failed short of reaching significance (p = .082, d = 0.67). Yet, with respect to learning, girls showed significantly smaller RMSE values than boys in the delayed retention test (p = .012, d = 1.00) and in the automation test (p = .045, d = 0.74). These results illustrate that girls possess an advantage over boys when learning a new dynamic balance task. Consequently, when training balance boys might be given more practicing time and/or easier tasks compared to girls.

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RESEARCH ARTICLE Open Access

Effect of practice on learning to maintain balance under dynamic conditions in children: are there sex differences?

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Abstract

Background: In youth, sex-related differences in balance performances have been reported with girls usually outperforming same-aged boys. However, it is not known whether sex also has an influence on learning of a new balance task in primary school-aged children. Therefore, the present study investigated sex-related differences in children learning to maintain balance under dynamic conditions.

Methods: Thirty-two children (16 girls, 16 boys) aged 8.5 ± 0.5 years practiced balancing on a stabilometer (i.e., to keep it as horizontal as possible) for seven trials (90 s each) on two consecutive days. Knowledge of results (KR) (i.e., time in balance) was provided after each trial. On day three learning was assessed using a retention test (i.e., balance task only) and a test of automation (i.e., balance plus concurrent motor interference task). Root-mean-square-error (RMSE) was recorded for all trials and used for further analysis.

Results: During practicing (Day 1, Day 2) RMSE values significantly decreased over the days ($p = 0.019$, $d = 0.92$) and trials ($p = 0.003$, $d = 0.70$) in boys and girls. Further, the main effect of sex showed a tendency toward significance ($p = 0.082$, $d = 0.67$). On day 3, the girls showed significantly smaller RMSE values compared to boys in the retention ($p = 0.012$, $d = 1.00$) and transfer test ($p = 0.045$, $d = 0.74$).

Conclusions: Performance increases during the acquisition phase tended to be larger in girls than in boys. Further, learning (i.e., retention and automation) was significantly larger in girls compared to boys. Therefore, practitioners (e.g., teachers, coaches) should supply boys and grils with balance exercises of various task difficulties and complexities to address their diverse learning progress.

Keywords: Youth, Skill acquisition, Stabilometer, Postural control, Human

Background

Balance is important during activities of daily life as well as in sports and poor balance is associated with an increased risk of falling and sustaining injuries [1]. This is particularly important for children as balance performance does not reach the adult-level before late adolescence due to maturation processes of the postural control system [2]. According to Shumway-Cook and Woollacott [3], a distinction is made between static balance where the base of support and the ground remain stationary and only the center of mass moves (e.g., standing on a firm floor) and dynamic balance where the base of support and/or the ground move and the center of mass shifts (e.g., walking). Further, it is differentiated between proactive (i.e., anticipation of a predicted perturbation) and reactive (i.e., reaction to an unpredicted perturbation) balance. All these components are reportedly independent from one another indicating that a

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person can exhibit sufficient balance performance during static conditions but perform poor in a dynamic or reactive balance task [4]. As most daily activities (e.g., climbing stairs) are rather dynamic in nature, sufficient balance during dynamic conditions is essential for everyday life.

With respect to balance performance in youth, findings on sex-related differences are rather inconclusive. For example, a systematic review with meta-analysis [2] examining age- and sex-related differences in balance performance in youth found inconsistent results. More precisely, girls showed superior static balance (standardized mean difference [SMD] = 0.33), while boys performed better in proactive conditions (SMD = − 0.15) and almost no difference was found concerning measures of dynamic balance (SMD = − 0.02). Yet, the largest difference was found in favor of girls and this comparison was based on the results of 16 different studies whereas far less studies were available for comparisons of dynamic steady-state balance (n = 7) and proactive balance (n = 6). Thus, it may be speculated that if existent at all sex-related differences in balance performance in youth may be more likely in favor of girls. In studies which found sex-related differences in balance performance in youth, those have been attributed particularly to the development of the postural control system as girls are known to mature earlier than boys [5, 6]. Yet, there might be other influencing factors such as higher agitation in (younger) boys [6], differences in neural maturation as for instance the total cerebellar volume peaks earlier in girls compared to boys [7], or sports participation (e.g., type and/or amount of sport). However, although girls participate in sports involving lots of balance (e.g., gymnastics) more frequently than boys [8], a study investigating sex differences in balance performance in youth gymnasts [9] still found superior balance performance in female compared to male youth gymnasts.

Practicing a new motor skill leads to short-term adaptations resulting in improved performance in this particular motor skill with repeated trials. If sufficient practice is given during this acquisition phase, long-term adaptations indicating learning can be observed during retention and transfer tests [10]. These tests are usually carried out 24 h after the last practice session so that short-term adaptations from the acquisition phase can dissipate and involve the execution of the practiced task under slightly different conditions (e.g., no feedback) [11]. If actual learning has been achieved, performance under the changed conditions should still be better than at the beginning of the acquisition phase. This relation has been documented in various experiments including fine as well as gross motor skills [10]. Several studies in the field of motor learning applied balance tasks [12–15] using a stabilometer [12, 13], wobbleboards [14], or pedalos [15]. Generally, these studies showed that during the acquisition phase performance improved with practice in adults as well as in children and induced learning of the practiced balance task as indicated by still improved performances in retention and transfer tests. For instance, Becker and Smith [15] observed practice-related improvements in primary school-aged children (8–10 years) and young adults (19–26 years) during 20 practicing trials on a double pedalo followed by a 24 h delayed retention test. More specifically, time to complete a seven meter course on the pedalo significantly decreased with practice and was still improved in the retention test.

Research on motor learning in children using balance tasks has predominantely focused on the influence of focus of attention (internal vs. external) and studies on sex-related differences regarding balance in youth have mostly focused on performance. Yet, besides differences in balance performance between girls and boys there might also be sex-related differences in learning of a balance task. Knowledge about such differences is of major importance for practitioners such as teachers or coaches, for example to specifically design training programs in terms of task difficulty and/or task complexity level. Therefore, the present study aimed to investigate the influence of practice on learning to maintain balance under dynamic conditions in primary school-aged children, also including sex-related differences. Due to the previously reported involvement of maturation, we opted for primary school-aged children to exclude adolescent growth as a potentially confounding factor. We hypothesized, that a) practice leads to short-term adaptations resulting in improved performance in the practiced balance task and that b) improvements will be larger in girls compared to boys. Additionally, we hypothesized that practicing would induce learning and that girls would show better performances than boys in delayed retention and automation tests.

Methods

Participants

Thirty-two children (16 boys, 16 girls) with a mean age of 8.5 ± 0.5 years from two local primary schools participated in the study. Table 1 shows group means and standard deviations for chronological age, body height, body mass, leg length, and maturity offset according to sex. Maturity offset was calculated in terms of years from peak height velocity (PHV) for each participant by using the formula provided by Moore et al. [16].

As verified by participant's parents report, none of the children had any neurological, orthopedic, or musculoskeletal disorder that could have affected their ability to follow the instructions and/or execute the applied tasks. Furthermore, we assured that none of the children had prior experience with the balance task and/or regularly

Table 1 Characteristics of the children included in the study and *p*-values for comparisons between girls and boys

	Girls (*n* = 16)	Boys (*n* = 16)	*p*-value
Age (years)	8.5 ± 0.5	8.6 ± 0.5	.733
Body height (cm)	136.3 ± 6.3	139.2 ± 6.6	.208
Body mass (kg)	32.0 ± 6.3	33.0 ± 5.8	.650
Leg length (cm)	72.8 ± 4.6	74.8 ± 3.7	.193
Maturity offset[a] (years from PHV)	−2.81 ± 0.46	−3.69 ± 0.41	.000

Values are presented as means ± standard deviations. [a]Maturity offset was calculated by using the formula provided by Moore et al. [16]. *PHV* peak height velocity

performed balance training (e.g., tightrope walking) as this could have affected training improvements. All measurements were performed in a separate room within the school building, with only one participant being present at a time.

Experimental procedure

Acquisition (day 1 and 2)

After anthropometrics were measured, participants were instructed to balance on a stability platform (Lafayette Instrument, Model 16,030, Lafayette, LA, USA). The platform (stabilometer) consisted of a swinging wooden platform (65 × 107 cm) which allowed a maximum deviation of 15 degrees to either side of the horizontal plane of the platform (Fig. 1). To prevent participants from falling in case they lost balance a safety rail mounted to the stabilometer was used.

Participants trained on the stabilometer during two consecutive days. Each session consisted of seven trials lasting 90 s separated by 90 s rest periods. All participants were instructed to balance on the stabilometer in order to keep the platform horizontal (± 3 degrees) while gazing at a fixed target approximately one meter opposite to the platform. Trials started from a horizontal position with participants holding on to the safety rail (Fig. 1a). After each trial, participants received knowledge of results (KR) (i.e., time in balance). Participants had to stepp off of the platform after each trial and were asked to step back on it approximately 20 s before the start of the next trial.

Testing (day 3)

Because performance changes during the acquisition phase (days 1 and 2) may only reflect temporary changes, a delayed retention and automation test was carried out to assess learning of the balance task. Procedures during retention test were identical to the acquisition phase, yet participants did not receive KR anymore.

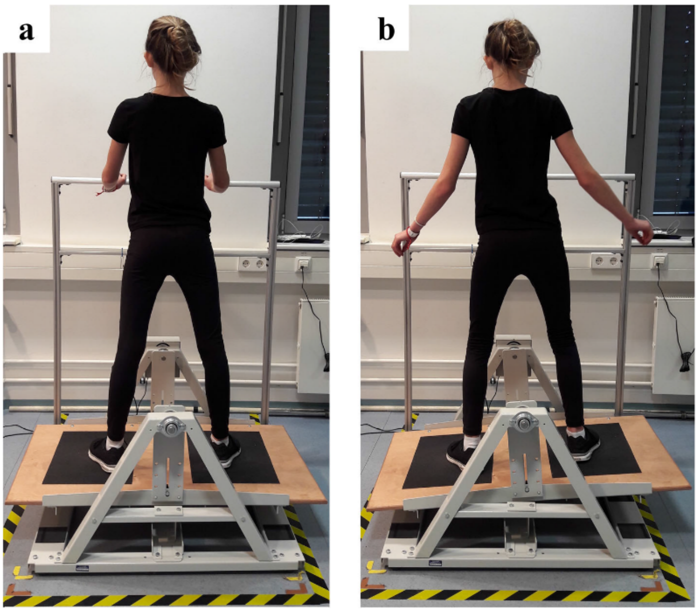

Fig. 1 Illustration of a child standing (**a**) and balancing (**b**) on the stability platform (stabilometer). Note. The individual that is shown and its legal guardians have given written informed consent to publish these case details

Thereafter, an automation test took place, which involved the execution of an additional motor interference task. Participants were asked to hold two connected metal rings in a way that they did not touch each other while balancing on the platform. For the retention and automation test, three trials à 90 s with 90 s rest between trials were performed and no KR was provided.

Data collecting

A timer sampling platform data at a rate of 25 Hz was used to measure time in balance. A platform angle within ±3 degrees of the horizontal position was defined as ´in balance´. Furthermore, PsymLab Software (Lafayette, LA, USA) was used to export platform position data and calculate the root-mean-square-error (RMSE) of the stability platform angle in degrees which was used for further analyses.

Statistical analyses

An a priori power analysis using G * Power [17] with the following input parameters was performed to obtain a medium-sized interaction effect: effect size ($d = 0.50$), type I error ($\alpha = 0.05$), type II error ($1\text{-}\beta = 0.95$), number of groups ($n = 2$), number of measurements ($n = 7$), correlation between measurements ($r = 0.50$). Additionally, a dropout rate of 20% was considered. Our analysis revealed a total sample size of 31–32 participants. Descriptive statistics were presented as group means ± standard deviations (SD). Normal distribution was examined using the Shapiro-Wilk test ($p > 0.05$) and homogeneity of variances using the Levene's test ($p > 0.05$). During acquisition on day 1 and day 2, the RMSE values were analysed in a 2 (sex: boys, girls) × 2 (day: day 1 to 2) × 7 (trial: trial 1 to 7) analysis of variance (ANOVA) with repeated measures on days and trials. During testing on day 3, the RMSE values were separately compared between girls and boys for the retention and automation using a one-way ANOVA. All analyses were adjusted for the observed differences in maturity offset between girls and boys. Additionally, Cohen's d was calculated to determine whether a statistical difference was practically meaningful as small ($0 \leq d \leq 0.49$), medium ($0.50 \leq d \leq 0.79$), and large ($d \geq 0.80$). All analyses were performed using the Statistical Package for Social Sciences (SPSS) version 24.0 and significance level was set at $p < 0.05$.

Results

No significant differences regarding age and anthropometrics (i.e., body height, body mass, leg length) were found between boys and girls. However, girls were significantly closer to reaching PHV than boys (Table 1).

Acquisition (day 1 and 2)

Generally, there were no statistically significant differences ($F_{(1,\ 30)} = 1.630$, $p = 0.212$) at the start of the experiment (i.e., first trial performance at day 1) between girls and boys. As can be seen from Fig. 2, both the boys and the girls decreased their RMSE values across the 2 days of practice. The adjusted Sex × Day × Trial ANOVA revealed statistically significant main effects of day, $F_{(1,\ 30)} = 6.171$, $p = 0.019$, $d = 0.92$ and trial, $F_{(6,\ 180)} = 3.527$, $p = 0.003$, $d = 0.70$. Further, we detetcted a tendency toward significance for the main effect of sex, $F_{(1,\ 30)} = 3.247$, $p = 0.082$, $d = 0.67$ with girls showing smaller RMSE values during acquisition compared to boys. Yet, we did not find a significant Sex × Day × Trial interaction, $F_{(6,\ 180)} = 0.535$, $p = 0.739$, $d = 0.27$, indicating

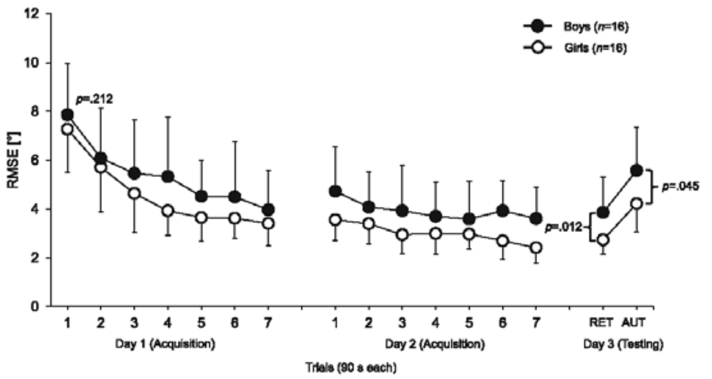

Fig. 2 Root mean square error (RMSE) for the boys (filled circles) and girls (unfilled circles) during acquisition (day 1 and day 2) and during testing (day 3). Values represent means and standard deviations. RET = means of three retention test trials (i.e., balance task only); AUT = means of three automation test trials (i.e., balance task plus concurrent motor interference task)

that improvements on day 1 and on day 2 were not sex-specific.

Testing (day 3)

Girls compared to boys showed significantly smaller mean RMSE values in the retention, $F_{(1,\ 30)} = 7.248$, $p = 0.012$, $d = 1.00$ and automation test, $F_{(1,\ 30)} = 3.982$, $p = 0.045$, $d = 0.74$ (Fig. 2).

Discussion

In the present study, we examined the influence of practice on learning to maintain balance under dynamic conditions in primary school-aged children and investigated whether there are differences between girls and boys. Our findings can be summarized as follows: (i) with practice, performance of the trained balance task improved with a tendency toward significantly better performances in girls than in boys; (ii) learning of the new balance task was larger in girls compared to boys, as indicated by their superior performances during retention and automation tests.

The observed increase in performance throughout practicing and subsequent learning of the balance task is in line with previous findings on motor learning in adults [12, 13] as well as in children [18]. However, we found a tendency toward significance but no significant differences in short-term adaptations between boys and girls during the acquisition phase on the first 2 days of practicing. This finding is in contrast to a study of Fujiwara et al. [19]. These authors investigated short-term adaptations to floor oscillations over five consecutive trials in children aged four to 12 years. Results showed that girls were able to adapt to floor oscillations from age five on as indicated by decreased center of pressure (CoP) speed over trials whereas the same development was only seen in boys from age six onwards. Additionally, in 7–8-year-olds CoP speed in girls was significantly smaller at the end of the acquisition phase than in boys. However, our study also included children aged 9 years and Fujiwara et al. [19] did not find sex-related differences in 9–10-year-olds as well. Additionally, although the sex-effect during practicing did not reach significance in our analysis, there was a strong tendency toward it as indicated by the p-value of 0.058 and the moderate effect size of 0.72.

Several studies reported associations between neuromuscular activity and improved balance performance [14, 20, 21]. For example, Brueckner et al. [20] used the same stabilometer task in young adult males (26 ± 6 years) and applied surface electromyography (EMG) on the tibialis anterior (TA) and gastrocnemius (GM) muscles. In addition to the performance increase in terms of reduced movement error with practice and subsequent learning, results yielded significantly decreased overall EMG intensity in the TA and GM over the 3 days. Authors concluded that increased movement efficiency during the balance task may account for improved performance in young adults. The same or at least similar mechanisms might explain the present findings in children. However, we abstained from using surface EMG as we examined primary school-aged children in a regular school setting, which delimitated our testing procedures in terms of time and complexity. Moreover, Taubert et al. [22] reported rapid region-specific addaptations of the motor cortex to balance training indicated by significantly increased cortical thickness after a single training session in young adults. Future studies on learning of a balance task in children should therefore at least consider to use surface EMG or functional magnetic resonance imaging (fMRI) to get a better understanding of adaptational processes to motor practice and learning in children.

Both, girls as well as boys, exhibited learning of the new balance task as indicated by their performances during retention and automation tests (Fig. 2). Further, these effects were larger in girls compared to boys. In children, boys reportedly show higher levels of agitation and are usually less attentive than girls especially during balance tasks [23, 24]. This is in line with our observations during the test procedure. For instance, girls stayed quite focused throughout all practice trials trying to balance on the stabilometer as good as possible. Contrary, several boys started asking questions to the experimenter or turned their heads to look around while balancing on the stabilometer. However, especially when practicing a new balance task it is important to concentrate sufficiently. Although, the experimenter did not respond to questions and reminded boys to focus on the mark at the wall as soon as they got distracted these factors may have impeded boys` performance improvements during the acquisition phase to some degree. Nevertheless, they still achieved learning of the task.

Besides these behavioral or psychological explanations, it has been argued that advanced neural maturation may explain superior balance performance of girls. For instance, the total cerebellar volume peaks approximately 2 years earlier in girls than in boys [7]. Similar findings have been reported for gray matter volume [25]. All of these structures are reportedly involved in postural control and balance performance [26]. From a developmental viewpoint, girls in our study were more mature than boys as indicated by the time to PHV and we observed better learning of a new balance task under dynamic conditions in girls compared to boys. Thus, our results corroborate the hypothesis that advanced neural maturation in girls may not only promote balance performance but also facilitate balance learning.

Balance is an important motor skill for children to cope with activities of daily life (e.g., jumping, cycling) as well as in sports performance (e.g., gymnastics, team sports). As balance performance in children is limited due to their still maturing postural control system and poor balance is associated with an increased risk of falling and sustaining an injury, previous research has focused on balance trainability of children. A systematic review with meta-analysis [27] did not find sex to have a significant influence on balance trainability. However, the researchers emphasized the preliminary character of their findings as they observed a lack of high quality studies on this topic. Despite the research on balance trainability in children there has been a void of studies focusing on possible sex differences in children learning a new balance task. In this study, we found that girls show better learning compared to boys. This has important implications for practitioners such as teachers or coaches. On the one hand, boys might need more time to practice a balance task compared to same aged girls. On the other hand, practitioners should have a large repertoire of exercises of various difficulties and/or complexities to keep individuals challenged and facilitate learning progress.

There are a few limitations with this study that have to be addressed. First, we did not apply surface EMG or fMRI and therefore can only speculate on the underlying mechanisms of observed adaptations. Especially, with respect to the differences concerning learning of the balance task between girls and boys, the application of surface EMG or fMRI might have provided deeper insights. Further, we neither assessed participants' motor nor cognitive development at baseline. As motor as well as cognitive development may have affected participants' progress in the balancing task, these variables could have been added as covariates in the analysis, thus providing deeper insights into interrelations between motor development, cognitive development, and motor learning. Additionally, the balance task is rather artificial, which limits the transferability of our findings to everyday life situations. Moreover, the presented results only apply to primary school-aged children in the investigated age-group. Future studies are advised to also compare youth of different age-groups as balance performance increases with age. It has been supposed that boys possess an advantage over girls concerning motor skill learning from 9 years onwards, although this finding was limited to manual dexterity [28]. In our study, girls performed significantly better than boys in the delayed retention test. However, this test was carried out 24 h after the last practice and future studies should also investigate sex differences in the performance of the applied balance task following longer retention phases (e.g., 1 week, 1 month). Lastly, possible sex-differences in short-term adaptations (i.e., during practice) need to be clarified as our results indicated a tendency toward a significant sex-effect in favor of girls.

Conclusions

Practicing a new balance task improved performance and lead to learning of this task in primary school-aged girls and boys. Yet, learning was larger in girls than in boys. Advanced neural maturation in girls as well as higher attention and less agitation might explain these findings. Practitioners such as teachers or coaches should pay attention to these differences when designing training regimes or assessing learning progress and possess a large repertoire of balance exercises with various difficulties and complexities to facilitate learning.

Abbreviations

ANOVA: Analysis of variance; CoP: Center of pressure; EMG: Electromyography; fMRI: functional magnetic resonance imaging; KR: Knowledge of results; PHV: Peak height velocity; RMSE: Root-mean-square error; SMD: Standardized mean difference

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Authors' contributions

SS and TM designed the research question. SS and DB conducted the testings and data collections. SS, TM, and RK analysed the data. SS and TM wrote the main parts of the manuscript. All the authors contributed to critical review of draft manuscripts and approved the final manuscript.

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Availability of data and materials

The data collected and analysed in the present study are not publicly available due to ethical restrictions but are available from the corresponding author upon request.

Ethics approval and consent to participate

The Human Ethics Committee at the University of Duisburg-Essen, Faculty for Educational Sciences approved the study protocol. Before experimental procedures began, participants' assent and parents' written informed consent were obtained.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests. TM is an Editorial Board Member of BMC Sports Science, Medicine, and Rehabilitation.

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5 General Discussion

Within the framework of this doctoral dissertation four original studies including one systematic review with meta-analysis, one cross-sectional study, and two intervention studies were conducted to obtain a deeper understanding on how age and sex affect balance performance and the trainability of balance in healthy children and adolescents. The main findings can be summarised as follows:

(1) Overall, adolescents show superior static steady-state, dynamic steady-state, and proactive balance performance compared to children.
(2) In children, adolescents, and young adults, relationships between types of balance (i.e., static/dynamic steady-state, proactive) are small and only slightly affected by age.
(3) Balance training is effective in children as well as in adolescents, however children seem to benefit more than adolescents.
(4) Findings on the effect of sex on balance performance in youth are ambiguous as girls show superior performance under static conditions, whereas boys perform better during proactive balance tasks and with respect to dynamic steady-state balance differences are negligible.
(5) Although short-term adaptations during the practice of a new dynamic balance task are similar in pre-pubertal girls and boys, long-term effects indicating learning of this task are larger in girls compared to boys.

In the following chapters, these results will be discussed and integrated into the existing body of knowledge. The role of age and sex will be discussed separately with respect to balance performance and the trainability of balance.

5.1 The influence of age on balance performance and balance trainability in youth

Two studies (i.e., STUDY I, II) included in this doctoral thesis investigated the effects of age on balance performance and associations between types of balance in youth. Overall the results indicated superior balance performance of older (i.e., adolescents) compared to younger (i.e., children) individuals, whereas associations between types of balance were small in all age groups investigated and only marginally affected by age (i.e., STUDY II). Additionally, one study (i.e., STUDY III) examined whether age affects the benefits of balance training in youth and findings indicated that balance training is probably more effective in children as compared to adolescents. In the following two chapters the role of age will be discussed in detail with respect to balance performance and balance trainability, respectively.

5.1.1 Age-effects on balance performance in youth

Consistent with the first research hypothesis, the results of STUDY I indicated better static ($SMD = 1.20$) and dynamic steady-state ($SMD = 0.26$) as well as proactive ($SMD = 0.28$) balance performance of adolescents compared to children. However, these findings were derived from the statistical comparison of the results of a number of cross-sectional studies which showed substantial to considerable heterogeneity ($59\% \leq I^2 \leq 91\%$) with respect to the tests applied, the measures used, and the age as well as the number of participants. Therefore, one aim of STUDY II was to replicate these findings using identical testing procedures in groups of healthy children, adolescents, and young adults. Supporting the findings of STUDY I, adolescents showed significantly better static steady-state and in parts (i.e., maximal normalised reach distance of the Y-balance test in posteromedial direction) proactive balance performance compared to children. Yet in contrast to STUDY I, no differences were observed regarding dynamic steady-state balance. Overall, these findings indicate that the development of postural control continues into adolescence which is in contrast to studies suggesting balance performance to be adult-like already in children [23, 112].

What are likely explanations for the observed findings? In youth, improved balance performance has been attributed to enhanced sensory integration [26, 27, 76, 113-115], changes in postural control strategy [64, 65, 68, 116, 117], and advanced neural maturation [5, 24]. Interestingly all of these developments continue into adolescence. Regarding the use of sensory information it has for instance been shown that the ability to use somatosensory input matures rather early at the age of three to four years, while it is not before mid-adolescence (i.e., 15-16 years) that visual and vestibular function reach their full potential [26, 27]. Further, the ability to task-dependently choose between different postural control strategies has to be acquired during youth. For example, during quiet stance children initially control balance using fast, ballistic movements before they switch to a strategy using slower but more accurate postural adjustments and finally are able to combine both strategies when growing up [68, 117]. Additionally, balance performance is considered to be associated with various central nervous structures such as the cerebellum, basal ganglia, or thalamus [118]. In this context, it has for instance been shown that deteriorations of cerebellar white matter are related to decreased postural control in young people (8-19 years) with traumatic brain injury [119]. Conversely, performance increases following balance training are accompanied by structural alterations of the cerebellum in this population [120]. Central nervous structures including the cerebellum are known to develop throughout adolescence [121] and may therefore also contribute to age-related increases in balance performance in youth.

Other explanations for better balance performances of adolescents compared to children may be increased muscular strength and/or larger attentional resources. More specifically, some balance tests (e.g., Functional reach test) are associated with lower extremity muscle strength in youth [28] which increases with maturation as well [32]. Thus, older individuals (e.g., adolescents) may possess an advantage over younger ones (e.g., children) in these tests. Further, it has also been hypothesised that especially for younger children it might be too challenging to consistently meet the attentional demands required during balance tests [38, 86]. As implemented by Waelchli et al. [38], it may therefore be suitable to shorten the length and/or number of trials when balance is assessed in children.

To summarise, based on the presented findings the development of balance control does not terminate during childhood but continues at least into adolescence due to the various maturational factors described before. However, maturation shows considerable variation between individuals even of the same age [32]. Consequently, it is not surprising that in youth biological age seems to be a better predictor of balance performance than chronological age [122-124]. Unfortunately, so far most studies have not reported biological age which should become a standard in future studies on balance performance in youth. Lastly, it should be noted that no studies investigating reactive balance performance in youth met the inclusion criteria of STUDY I. From a practical point of view, reactive balance is much more important than for example static balance as humans are inherently moving creatures interacting with an often unpredictable environment. Accordingly, sufficient reactive balance performance is extremely important for instance to avoid falls following unexpected postural disturbances such as trips or slips. Consequently, results of STUDY I also highlight that high-quality studies on reactive balance performance in children and adolescents are much-needed.

Besides age-related performance differences, previous research also indicated that types of balance (e.g., static, dynamic) are independent of each other leading to the conclusion that balance is task-specific [28, 29, 56, 125]. However as described before, in youth the postural control system is still developing due to maturational processes. Moreover due to lower levels of movement experiences, motor control in younger individuals (e.g., children) may be less specific than in older youths (e.g., adolescents) [126]. In the second research hypothesis it was therefore stated that associations between types of balance would be overall small in children, adolescents, and young adults, but larger in younger (e.g., children) as compared to older (e.g., adolescents, young adults) individuals.

The first part of this hypothesis was confirmed by small-sized ($-.302 \leq r \leq .245$) and non-significant ($p > .05$) correlations between measures of static, dynamic, and proactive balance performance in children, adolescents, and young adults (i.e., STUDY II). The only exception was found for one out of 21 correlation coefficients which indicated a statistically significant association between types of balance. More specifically, in young adults, proactive balance performance (i.e., composite score of the Y-balance test) was positively associated ($r = .319$, $p < .05$) with one measure of static steady-state balance performance (i.e., M/L sway). These findings are in accordance with other studies which reported non-significant relations between types of balance in children [28, 50], adolescents [29], and young adults [55]. Thus, already in children balance seems to be task-specific, indicating that balance is not a "general ability" and that types of balance should be trained and tested individually/complementary in all age groups investigated. Possible explanations relate to the diverse challenges different balance tasks pose to the postural control system including the nature of the balance task (e.g., difficulty, complexity) and/or the neurophysiological mechanisms involved (e.g., strategy use). For instance, compared to dynamic tasks such as walking the degrees of freedom are limited during static standing on stable ground and thus less attentional demands are required [127]. Additionally, while under proactive conditions postural control has to be organised in advance of an anticipated perturbation, balance has to be maintained in response to unexpected disturbances during reactive balance tasks [128]. Thus, the former requires feedforward control, whereas the latter necessitates feedback control.

As stated in the second part of the research hypothesis, associations between types of balance were expected to be larger in younger as compared to older participants due to the immaturity of the postural control system and lower levels of motor experience. In contrast to this assumption, 19 of the 21 comparisons did not show statistically significant differences of associations of types of balance between children, adolescents, and young adults. More importantly, one comparison even revealed a smaller association between one parameter of static steady-state (i.e., M/L sway) and proactive balance performance in adolescents (r = -.131) as compared to young adults (r = .319). In fact, solely the association between dynamic steady-state and proactive balance performance was significantly larger in children (r = -.302) and adolescents (r = -.276) as compared to young adults (r = .161) lending support to the hypothesis that children and adolescents may be able to switch between the execution of different motor tasks (incl. balance) as they represent individuals "early in practice" [126]. These findings are in contrast to the results of a systematic review and meta-analysis on age-related differences in associations between types of balance [30] which reported smaller associations of static and dynamic balance in children (7-13 years) as compared to old adults (≥ 65 years) and hypothesised that in youth age and maturation may affect associations between types of balance. However, the authors [30] emphasised that their analysis might have been biased by methodological inconsistencies between single studies.

Although in STUDY II no "old adults" were included, the finding of predominantly non-significant differences of associations between types of balance performance between age groups after conducting identical testing procedures in all age groups investigated underpins this assumption. Consequently, the influence of age and thus maturation on associations between types of balance in youth seems to be extremely limited. Thus, regardless of age, types of balance should be trained and tested individually or complementary in youth.

5.1.2 Age-effects on balance training in youth

Based on the assumption that age-related differences in balance performance in youth may also affect the trainability of balance, in STUDY III [42] a field-based approach was used to examine the effects of a standardised balance training program in children and adolescents. Largely confirming the third research hypothesis, balance training was effective to improve static (only in children) and dynamic steady-state balance (in children and in adolescents) performance, with larger improvements in children compared to adolescents. However, no training-related improvements were found for most measures of proactive (except the normalised maximal posterolateral reach) and reactive balance in neither age group. First, these results will be integrated into the existing literature for children and adolescents separately, before age-dependent differences will be discussed.

With respect to children, Granacher et al. [86] did not find significant performance increases during a quasi-dynamic balancing task (i.e., two-legged stance on foam ground on a balance platform with eyes open) in six-to-seven-year-old children following four weeks of balance training conducted during regular P.E. lessons. In contrast, Donath et al. [83] reported significant increases in standing times on a slackline in ten-year-olds who trained on this device for six weeks. These inconsistent results were attributed to age differences and thus maturational differences between participants of both studies [83, 86]. More specifically, the age-range of six to seven years has been considered to represent a milestone in the development of postural control [23, 65] as evident for example by distinct decreases in postural sway velocities in children aged seven to eight years [65]. Thus, it was argued that children in the study by Granacher et al. [86] may have lacked an important neurophysiological prerequisite for adaptations to balance training. However, contradicting this view Waelchli and colleagues [38] observed improved dynamic balance performance already in children as young as six years following five weeks of child-oriented balance training. One explanation for these diverging results may relate to the design of the respective training program, which was specifically tailored to have challenging character for young children in the study by Waelchli et al. [38], whereas Granacher et al. [86] used common balance exercises and observed that many children struggled to stay concentrated throughout the training which may have limited its effectiveness. In contrast to the study by Granacher et al. [86] and supporting the findings by Donath et al. [83] and Waelchli et al. [38], in STUDY III five weeks of balance training were effective to significantly increase static and dynamic steady-state balance performance in seven-year-old children. Thus, the immaturity of the postural control system in young children does not seem to inhibit adaptations to balance training.

Concerning adolescents, Emery et al. [87] were able to show that compared to a control group static (i.e., one-legged stance standing time with eyes closed on firm ground) and quasi-dynamic (i.e., one-legged stance standing time with eyes closed on foam ground) balance significantly improved in adolescents (14-19 years-old) who conducted a progressive, home-based balance training program for six weeks. Similarly, Granacher et al. [88] observed significantly improved static steady-state balance performance (i.e., reduced postural sway during one-legged stance on a balance platform) in 19-year-old adolescents following four weeks of balance training. These findings are largely supported by results from STUDY III which revealed significantly improved dynamic steady-state balance performance in 14-year-olds following five weeks of balance training. However, in contrast to the aforementioned studies no changes were found for measures of static steady-state balance. Similar observations were reported by Waelchli et al. [38] who did not find training-related improvements in static balance performance in neither children nor adolescents which was attributed to possible ceiling effects as the applied tests were rather easy (i.e., tandem stance, Romberg stance). Although a more difficult test (i.e., one-legged stance on a force platform) was used to assess static balance performance in STUDY III, no performance improvements were observed in adolescents. One explanation may be that the applied test was still too easy for the “older” participants (i.e., adolescents) and thus created a ceiling effect. Indeed, adolescents’ performances in the static balance test were already on a high level at baseline. Consequently, compared to children they had less adaptive reserves and it may also be speculated that the static exercises conducted during the training program of STUDY III were not difficult enough to adequately challenge the adolescents’ postural control system.

As stated before, the majority of previous studies on the effectiveness of balance training in youth has either focused on children [83, 86] or adolescents [87, 88], but there has been a void in the literature on age-dependent adaptations to balance training in youth. In fact, only three studies [38, 39, 90] investigated the effectiveness of balance training in youth with respect to different age groups. Although standardised mean differences calculated in a systematic review and meta-analysis [90] indicated that balance training is more effective in children (*SMD* = 1.28) compared to adolescents (*SMD* = 0.84), this difference failed to reach significance. Further, when comparing the effects of child-oriented balance training on static and dynamic balance performance in three groups of children and adolescents (i.e., 6-7 year-olds, 11-12 year-olds, 14-15 year-olds) Waelchli et al. [38] found significant improvements in dynamic balance performance that were larger in the youngest (i.e., 6-7 year-olds) compared to the two older (i.e., 11-12 and 14-15 year-olds) age groups. Lastly, in another study [39] five weeks of child-oriented balance training resulted in improved performances following anticipated (direction known) and unanticipated (direction no known) perturbations in six year-old children as well as in twelve year-old adolescents. Yet, even though children showed larger adaptations in the unanticipated condition, whereas improvements in the anticipated condition were larger in adolescents, these differences were not statistically significant [39].

The results of the systematic review and meta-analysis [90] were derived from single studies which predominantly examined effects of balance training on different types of balance (e.g., static or dynamic) in either children or adolescents. Additionally, in the two intervention studies [38, 39] the authors failed to adjust their analyses for baseline differences between groups. Thus, previous findings on age-dependent adaptations to balance training in youth were limited due methodological flaws. STUDY III [42] aimed to overcome these objections by assessing all types of balance (i.e., static/dynamic steady-state, proactive, reactive) using the same standardised tests and conducting the same training regime in both children and adolescents. Thus, methodological inconsistencies between previous studies on balance training in youth which focused on single age groups (e.g., either children or adolescents), measured different types of balance (e.g., static or dynamic), and/or used various balance tests and measures were eliminated. Thereby, it was possible to assess the effect of age on adaptations to balance training in youth. Supporting the findings from previous studies [38, 90], the results indicate that with respect to static steady-state balance, performance increases following balance training are larger in children as compared to adolescents. Consequently and in contrast to the hypothesis of Granacher et al. [86] the immaturity of the postural control system in children does not seem to prevent adaptations to balance training but rather increase its effectiveness. This may be explained by the larger adaptive reserves of the structures involved (e.g., central nervous system, sensorimotor function) in postural control which mature throughout childhood and into adolescence (for details see chapter 5.1.1). Hence, it seems reasonable to regularly conduct balance training in P.E. lessons and sport-specific training regimes already with primary school-aged children.

What could be possible explanations for observed increases in balance performance following balance training? As STUDY III [42] was conducted in the regular school setting no neurophysiological data (e.g., surface electromyography, electroencephalography) were collected to investigate underlying adaptation mechanisms to balance training in children and adolescents and unfortunately such studies are scarce. In fact, to date there is only one study [129] which addressed this issue. Taube et al. [129] longitudinally assessed neurophysiological adaptations to balance training in fourteen-year-old elite athletes (i.e., ski jumping, nordic combined) during perturbed standing using surface electromyography and found reduced reflex responses of the soleus muscle (i.e., reduced H-reflex amplitude, decreased Hmax/Mmax ratio) after training. It was hypothesised that spinal activity decreased due to presynaptic inhibition of Ia-afferents and that with training movement control may be shifted from spinal to supraspinal centres. Although these findings are rather preliminary and evidence on age-dependent (e.g., children vs. adolescents) neurophysiological adaptations to balance training is lacking, current knowledge suggests that underlying mechanisms may be similar to those observed in young adults including adaptations on spinal (e.g., reduced reflex activity) [130] and supraspinal (e.g., decreased activity of the motor cortex) [131] levels. Simply put, while balance seems to be largely controlled by (automatic) reflex activity during new and/or demanding tasks, with training muscular activation can (consciously) be precisely tuned to keep the body balanced and this task becomes less demanding for the structures involved (e.g., motor cortex).

Finally, except for one measure of proactive balance (i.e., maximal normalised reach in the posterolateral direction) the applied training regime failed to improve measures of proactive and reactive balance in children as well as in adolescents. Regarding proactive balance, the results are in contrast to those of Waelchli and colleagues [39] who observed increased balance performances following an anticipated perturbation in children as well as in adolescents after five weeks of balance training. A possible explanation for these conflicting results may be derived from a study by Giboin et al. [132]. These authors [132] showed that training on either a tilt-board or a swinging platform (i.e., Posturomed) elicited adaptations only in the trained task, although both tasks are very similar in nature indicating that similar to the concept of task-specificity of balance performance, adaptations to balance training are also highly task-specific. Indeed, most of the weight-shifting tasks during the balance training of STUDY III consisted of arm-reaching tasks, whereas the test (i.e., Y-balance test) used a leg-reaching task. Additionally, it may be speculated that the exercises incorporating weight shifting tasks in STUDY III were not appropriate in terms of training difficulty (i.e., too easy) and/or training volume (i.e., too low) to increase performance in the Y-balance test. Concerning reactive balance performance, insignificant findings may be explained by the test used (i.e., Push-and-release test) as it has originally been developed for people with balance deficits (i.e., Parkinson's disease) [102] and may thus be unsuitable to detect subtle differences between healthy young individuals and/or following an intervention in a healthy population. Additionally, the control groups and the intervention groups in STUDY III showed similar improvements from pre- to post-test indicating a learning effect of the Push-and-release test in healthy youth. Nevertheless, to the best of our knowledge it is currently the only easy-to-administer, field-based test to assess reactive balance performance.

In conclusion, balance training can be considered an effective means to improve static/dynamic balance performance in healthy children and adolescents. In contrast to previous suggestions the immaturity of the postural control system in children does not seem to prevent adaptations to balance training but rather facilitates its effectiveness probably due to larger adaptive reserves. Consequently, already in childhood it seems reasonable to regularly include balance training or balance exercises in sport-specific training or P.E. lessons. Future studies should focus on the investigation of underlying mechanisms in order to clarify whether they are similar to those observed in adults (e.g., increased neuromuscular function). Finally, age-dependent adaptations to balance training in youth should further be investigated with respect to proactive and reactive balance as in STUDY III no improvements were found following the training applied, although these findings might result from methodological issues (e.g., tests used, training volume) and thus need further clarification.

5.2 The influence of sex on balance performance and balance trainability in youth

Two studies (i.e., STUDY I, IV) included in this doctoral dissertation investigated the role of sex on postural control in youth. One study (i.e., STUDY I) scrutinised the influence of sex on balance performance in children and adolescents and revealed equivocal results as compared to boys, girls showed superior static steady-state but inferior proactive balance performance, whereas the influence of sex on dynamic steady-state balance seemed to be negligible. The other study (i.e., STUDY IV) analysed how sex affects the acquisition and learning process of a new dynamic balance task in children. Although short-term adaptations during practicing were similar between boys and girls, long-term adaptations indicating a learning-effect were significantly larger in girls as compared to boys. Findings on the role of sex will be discussed separately for balance performance and balance trainability in the two following chapters.

5.2.1 Sex-effects on balance performance in youth

The fourth research hypothesis that girls show superior balance performance compared to same-aged boys was only partially supported by the results of STUDY I. More specifically, aggregating and analysing results from 21 studies on sex-related differences in balance performance in youth indicated better static steady-state balance performance in girls (SMD = 0.33), whereas boys showed better proactive balance performance (SMD = -0.15). Further, concerning dynamic steady-state balance performance differences between girls and boys were negligible (SMD = -0.02). However, the observed effect sizes were small (all $SMD \leq .49$).

Regarding individual development in youth, studies have shown sex-related differences. More specifically, in girls the onset and progression of physical, hormonal, and sexual developments are usually ahead of boys [32, 70, 71]. Interestingly, it has previously been shown that improvements in balance performance with age in youth can predominantly be attributed to maturational processes [59, 76] especially of central nervous structures [33] (also see chapter 5.1.1) and in fact the maturation of the central nervous system also shows sex-specific differences. For example, in girls the total cerebellar volume peaks on average at about 11.5 years which is approximately three years earlier than in boys [133]. Similarly, the development of subcortical grey matter volume (i.e., basal ganglia) follows an inverted u-shaped trajectory and peaks approximately 2.5 years earlier in girls as compared to boys [66]. However, although all of these structures are involved in the control of balance it is still not understood how exactly and to what extent they are interrelated with balance performance [118]. Additionally, physiological differences in brain structures do not necessarily imply that they result in any functional difference as for instance the total brain volume in healthy children can vary up to 50% between individuals [66]. Finally, most studies either investigate sex-related differences in balance performance or brain development in youth, but there is a paucity of research on relationships between these two parameters. In fact, such studies are to date only available for cohorts of healthy as well as impaired adults or seniors and transferring their results to healthy children and/or adolescents should be done with caution due to developmental differences.

Nevertheless, the findings of STUDY I revealed better performance of girls only during static balance tests, whereas boys showed superior proactive balance performance. Static balance tests typically require participants to stand as stable as possible usually on a force plate which records ground reaction forces to measure the centre of pressure displacement which is associated with postural sway. During this task, participants have to continuously analyse sensory input and produce fine-tuned muscular responses in order to keep the centre of mass within the base of support which also requires uninterrupted concentration. According to reports from Steindl et al. [26] and Hirabayashi & Iwasaki [27], boys seem to struggle considerably more with these challenges than girls. Additionally, although such biomechanical tests may have limited external validity, they provide excellent internal validity and may thus be most suitable to detect (subtle) performance differences between individuals of different sex, age, and/or performance level. On the other hand, proactive balance performance is frequently assessed using rather functional tests which often include reaching tasks while participants have to stay balanced. Besides these tests providing higher external compared to internal validity, they may also require sufficient muscular strength. In this regard Muehlbauer et al. [134] conducted a meta-analysis investigating associations between proxies of muscular strength and balance performance. Indeed, although these relationships were overall small in children and adolescents, in children maximal strength and muscle power were more associated with proactive ($0.41 \leq r \leq 0.54$) than with static ($0.11 \leq r \leq 0.21$) balance. Developmental studies have shown that during childhood and adolescence boys exhibit greater muscular strength than same-aged girls and this discrepancy increases with age in youth [32]. Therefore, better proactive balance performance of boys compared to girls may possibly be attributed to superior strength rather than to greater balance skills.

Further, results of STUDY I indicated that sex-related differences in dynamic steady-state balance performance in youth seem to be negligible. In four out of seven included studies investigating differences between girls and boys in this type of balance performance gait velocity was used for analyses. Associations between gait velocity and balance performance have predominantly been shown in seniors [135, 136] and it may therefore be speculated that this parameter is not distinctive enough in young healthy individuals. Alternative measures providing deeper insights into individual dynamic steady-state balance performance in youth could for example be stride-to-stride variability or time in single- and double-support during habitual walking.

Regarding the earlier maturation of girls it may be hypothesised that sex-related differences in balance performance might be especially pronounced in the transition from the first to the second decade of life, when girls have already entered puberty with its associated developments while boys still lack behind in terms of physical and neural development. Thus, one could speculate that sex-related differences in balance performance in youth might be more pronounced at this age, whereas in older adolescents disparities may be declining or have already disappeared. Supporting this view, García-Liñeira et al. [137] reported significant sex-related differences in balance performance during one-legged stance on unstable ground which were to the girls advantage and particularly prevalent between the ages of eight to eleven years. Therefore, in STUDY I single *SMDs* were also calculated for sex-related differences in balance performance with regard to different age groups (i.e., children vs. adolescents) and chronological ages. However, none of these calculations revealed age periods or ages where girls particularly outperformed boys or vice versa.

To summarise, depending on the type of balance there seem to be performance differences in some (e.g., static, proactive) but not all (e.g., dynamic) kinds of balance between girls and boys. Superior performances of girls may be explained by advanced maturation, whereas in boys they may result from secondary challenges (e.g., muscular strength) of the respective balance task. However, it has to be mentioned that with respect to the number of included studies and heterogeneity between them, evidence from STUDY I is more reliable concerning static steady-state balance (N = 16, I^2 = 23%) compared to dynamic stead-state (N = 7, I^2 = 40%) and proactive (N = 6, I^2 = 44%) balance. Finally, the unavailability of high-quality studies on sex-related differences in reactive balance performance in youth illustrates the imperative need for respective research.

5.2.2 Sex-effects on balance practice in youth

As stated in the fifth research hypothesis, practicing a new dynamic balance task was expected to cause short- as well as long-term adaptations in girls and boys and it was further assumed that these adaptations would be larger in girls as compared to boys. Consistent with this hypothesis, in STUDY IV performance increases illustrated short-term adaptations during the acquisition phase (i.e., days 1 and 2) and these could be retrieved under more challenging conditions (i.e., retention and automation test) indicating a learning-effect. However, and in contrast to the initial hypothesis, improvements during the acquisition phase were similar between girls and boys as indicated by a non-significant Sex × Day × Trial interaction (p = .082, d = 0.67). On the other hand, as indicated by statistically significant better performances in the retention (p = .012, d = 1.00) and automation (p = .045, d = 0.74) test girls exhibited better learning than boys which is in accordance with the hypothesis.

The finding of short-term (e.g., improved performance during practicing) and long-term (e.g., improved performance during retention/automation test) adaptations following the practicing of a novel motor task is in line with previous studies [79-81, 138]. However, these studies either investigated adults [79-81] or used a manual task [138]. In fact, only Fujiwara et al. [139] used a balance task in children (4-12 years) and reported some significant differences between girls and boys. More specifically, practice-related improvements (i.e., decreased centre of pressure sway) were observed in girls from age five years and boys from age six years onwards. Additionally, significant sex-related differences were found in seven-to-eight-year-olds where girls outperformed boys. These differences were attributed to the earlier development of postural control adaptation and the earlier maturation of central nervous structures in girls [139]. As participants in STUDY IV were slightly older (i.e., 8.5 ± 0.5 years) than the groups of children which showed performance differences in the study by Fujiwara et al. [139] it may be speculated that boys in STUDY IV also reached a certain developmental point explaining why there was only a tendency towards a significant interaction effect during the acquisition phase. Yet, it is important to mention that Fujiwara et al. [139] did not investigate the acquisition of a novel balance task but adaptations to periodic floor oscillations during an already mastered task (i.e., two-legged stance with eyes closed). Moreover, only short-term adaptations were analysed over five consecutive trials. Thus, comparing the results of Fujiwara et al. [139] with those of STUDY IV should be done with caution.

Although, boys and girls exhibited learning effects as evident by their still improved performances during the retention and automation test, these effects were larger in girls as compared to boys. Based on previous findings from developmental studies [32, 70, 71], it may be speculated that these differences can be attributed to advanced maturation of girls compared to same-aged boys. Concerning the development of the central nervous system it has for instance been shown that total cerebellar volume [133] and total grey matter volume [66] peak earlier in girls as compared to boys. More importantly, these structures are also of major importance for human posture control and motor learning [140]. For example, Diener et al. [141] reported significantly increased postural sway during two-legged stance in subjects with reduced cerebellar function (e.g., late cortical atrophy of the anterior lobe) compared to healthy individuals. Nevertheless, differences between girls and boys in STUDY IV were only evident when learning was assessed but not during the acquisition phase. Thus, while short-term adaptations proceeded similarly between sexes, long-term adaptations were more pronounced in girls which allows for two conclusions: On the one hand, the investigated study group may have been too small and/or too heterogeneous regarding their performance level as sex-related differences during practicing showed a tendency towards significance. On the other hand, it seems possible that in order to produce the same learning effects as in girls, young boys have to train more (e.g., training volume, training frequency, training duration).

To detect mechanisms explaining increases in motor performances during practicing of a new dynamic balance task (e.g., balancing on a stabilometer), previous studies have used surface electromyography (EMG) [142] and magnetic resonance imaging [143]. For example, Brueckner et al. [142] analysed muscular activity of the tibialis anterior and gastrocnemius muscle in young healthy males who practiced the stabilometer task using a similar approach as in STUDY IV. Their results indicated that performance increases were accompanied by reductions in EMG amplitude and EMG intensity of the tibialis anterior as well as the gastrocnemius muscle. Further, using wavelet analysis it was shown that with practice muscular activity in the low frequency band (i.e., 2-97 Hz ≙ wavelet 1-9) increased while it decreased in the high frequency spectrum (i.e., 118-322 Hz ≙ wavelet 10-17) in both muscles [142]. Thus, it was concluded that performance increases during practicing could be explained by an increased movement efficiency. Additionally, Taubert and colleagues [143] investigated grey matter changes in the motor cortex in participants who trained on the stabilometer and observed immediate (i.e., after a single session lasting 20 min), region-specific (i.e., regions representing the involved muscle groups), and steadily-evolving (i.e., over several practice sessions) increases in cortical thickness. Further, these adaptations were only found in response to balance training on the stabilometer but not after participants performed alternating lower limb movements which mimicked the balancing task indicating that brain structural changes resulted from the coordinative aspects of standing on the stabilometer. Even though the aforementioned studies provide insights into mechanisms explaining performance increases when practicing on the stabilometer, transferring their results to explain those of STUDY IV should be done with caution due to differences between participants. More precisely, Brueckner et al. [142] as well as Taubert et al. [143] investigated young healthy adults whereas STUDY IV was conducted with young children. As the postural control system of these younger individuals is still developing it cannot be ruled out that other mechanisms might account for observed performance increases. However, adaptations to balance training seem to follow similar processes in young adults and children/adolescents (also see chapter 5.1.2) and it may therefore be hypothesised that during practicing and learning of a new dynamic balance task in young children performance increases may be explained by increases in movement efficiency and changes in central nervous structures.

As has already been outlined in chapter 5.2.1, previous studies investigating sex differences in balance performance in youth reported higher agitation and distractibility in boys as compared to girls [26, 27, 59]. Similar observations were made in STUDY IV where many boys struggled to stay concentrated throughout the balance task, whereas girls seemed to stay rather focused. Although boys who showed signs of distraction (e.g., looking around, start talking) were reminded to stay concentrated, it cannot be ruled out that learning progress was limited due to these inattentive periods. However, in this regard results of STUDY IV are inconclusive. More specifically, during practice girls and boys showed similar performance improvements (although a tendency towards significance was found), but girls showed larger learning than boys. Thus, lower attention in boys would have only affected long-term but not short-term adaptations in response to practicing a new dynamic balance task which is at least questionable.

Lastly, based on the inverted pendulum model of the control of human posture [144] one may argue that the balancing task on the stabilometer is easier for smaller compared to taller individuals. Therefore, it is worth mentioning that there were no significant differences (p = .208) in body height between girls (136.3 ± 6.3 cm) and boys (139.2 ± 6.6 cm). Thus, the observed sex-related differences cannot be attributed to differences between girls' and boys' body stature.

To conclude, when practicing a new balance task, young boys may be given more time to achieve the same learning-effects as young girls. This information is especially important for practitioners such as P.E. teachers who may have to judge learning progress and/or sports coaches who design and conduct progressive training programs.

6 Practical Implications and Future Directions

The results of the studies included in this doctoral dissertation lead to several practical implications and offer the basis for future research aspects which will be presented in the following paragraphs.

Better balance performance of adolescents compared to children (i.e. STUDY I) indicates that the development of postural control is not completed in childhood but continues at least into adolescence. Therefore, balance performances of children and adolescents should not be compared between individuals of different ages or to those of adults whose postural control system has fully matured. Additionally, as improved balance performance is most likely explained by advanced neurophysiological maturation it is recommended to include measures of biological age which may be more closely linked to balance performance than chronological age when assessing balance performance in youth [122-124]. However, although there are significant differences in balance performances between children and adolescents, these age-related differences seem to have only minor effects on associations between types of balance (i.e., STUDY II). Consequently, already in children and adolescents balance seems to be task-specific indicating that types of balance should be trained and tested individually and/or complementary.

A standardised balance training is an effective means to improve measures of balance performance (i.e., static, dynamic) and as illustrated by the results of STUDY III, children may benefit more from such training than adolescents, probably due to the larger adaptive reserves. Sufficient balance performance is associated with a lower risk for sustaining falls [12, 13] and injuries [16-18] and is additionally considered to be an important component for several sports and sport-specific movements [22]. Therefore, it is recommended to regularly conduct balance training already with young children as performance increases seem to be particularly pronounced in this age group.

The results of STUDY I indicate that depending on the type investigated, balance performance differs between girls and boys. Therefore, clinicians or practitioners (e.g., paediatrician, P.E. teachers, sports coaches) should be careful when comparing balance performances between sexes in youth. The observed performance differences may also indicate that girls and boys should be provided with balance exercises of various difficulties to meet the individual abilities. For example, girls may be able to perform more difficult static balance exercises, whereas boys can be given proactive balance exercises of higher difficulty. Conversely, it may be reasonable to put stronger emphasis on static balance exercises in boys and proactive balance training in girls.

Following the practicing of a new dynamic balance task, larger learning effects were found in young girls as compared to same-aged boys (i.e., STUDY IV). Further, a tendency toward a significant sex-difference to the girls' advantage was found during practicing and it may thus be speculated that even short-term adaptations during the acquisition of a new balance task are larger in girls as compared to boys. Therefore, in children boys may need a longer practicing period than girls to achieve similar prolonged and probably also short-term effects. When designing progressive balance training programs girls may additionally proceed to more difficult exercises earlier than boys.

Besides these practical implications, the findings of the studies presented in this thesis can serve as a basis for future research. More specifically, the following starting points can be derived from the results of the conducted studies:

(1) In STUDY I-IV only behavioural data were imposed and analysed which do not provide clues about underlying mechanisms. Therefore, future studies on balance performance and/or balance trainability in youth should also include neurophysiological assessments (e.g., magnetic resonance imaging, electroencephalography, surface electromyography) although these methods are usually time- and cost-intensive due to the use of sophisticated instruments and often involve ethical issues when applied to minors.
(2) STUDY I-IV were limited to healthy, typically developed individuals. Thus, future studies should also investigate the role of age and/or sex on postural control in paediatric populations and/or scrutinise the role of (sport-specific) expertise level.
(3) There is currently a void in the literature (i.e., role of age and sex) on reactive balance performance in youth. Future studies are therefore advised to put stronger emphasis on this specific type of balance.
(4) Most studies on the development of balance performance in youth – including STUDY I and STUDY II – have used a cross-sectional design. However, to account for between-subject variability and in order to provide in-depth insights into the maturation of balance in youth longitudinal (monitoring) studies are needed.
(5) Although STUDY III and STUDY IV illustrated that balance training is effective in children and adolescents, it remains unclear how different load dimensions (e.g., training volume, training frequency, training duration) affect (age- and sex-

specific) adaptations to balance training in youth. Consequently, future studies should examine how altering these load dimensions affects adaptations to balance training in youth and how balance training should be designed in order to be most effective in youth. Further, in STUDY III the applied balance training failed to improve most measures of proactive and reactive balance performance. Future studies should clarify whether these findings reflect true facts or result from methodological issues.

(6) Finally, the investigated intervention periods in STUDY III and STUDY IV were rather short and thus only provide insights into short-term effects of balance training in youth. Consequently, future studies should also focus on long-term effects of balance training in youth.

These future directions will assist in the further understanding of the development of postural control and its trainability in youth, especially regarding the role of age and sex, respectively. Knowledge on the underlying mechanisms will further aid in the identification of suitable interventions. A deeper understanding of these relationships will help for instance in the identification of impaired individuals, talent identification or the design of effective training regimes.

7 Conclusions

The findings of the studies included in this doctoral dissertation constitute substantial contributions to the current knowledge on the influence of age and sex on balance performance and balance trainability in youth. Based on these results the following conclusions can be drawn:

(1) The development of postural control is not completed at the end of childhood but continues at least into adolescence indicating that age-related differences should be considered when balance performance is judged or tested or when balance training regimes are developed.

(2) Although the postural control system is still developing in youth, balance is task-specific already in children. Additionally, associations between types of balance are only marginally affected by age and thus maturational differences between children, adolescents, and young adults indicating that types of balance should be trained and tested individually/complementary from childhood onwards.

(3) Depending on the type of balance examined, sex-related differences in balance performance were found either in favour of girls (i.e., static steady-state balance) or boys (i.e., proactive balance), which are probably related to the different challenges these tasks pose to the postural control system. These differences should be considered when balance performance is judged or tested or when balance training regimes are developed.

(4) Balance training conducted during regular P.E. classes is an effective means to improve static/dynamic balance performance in children and adolescents. More importantly, the less developed postural control system in children does not seem to impede adaptations to balance training, but rather facilitates its effectiveness at least with respect to static/dynamic steady-state balance.

(5) Following the practice of a novel dynamic balance task, prolonged learning effects are larger in pre-pubertal girls compared to same-aged boys indicating that in children boys may be given more training volume to achieve similar long-term adaptations.

(6) So far studies on postural control in youth have largely disregarded reactive balance (perhaps due to methodological issues) which is, however, of major practical relevance and should therefore be scrutinised in future studies.

8 References

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9 Appendix

9.1 Author Contributions to STUDY I: *“Age and sex differences in human balance performance from 6-18 years of age: A systematic review and meta-analysis”*

Conceptualization: Rainer Kiss, Thomas Muehlbauer

Data Curation: Simon Schedler, Thomas Muehlbauer

Formal Analysis: Simon Schedler

Methodology: Simon Schedler

Writing – Original Draft: Simon Schedler

Writing – Review & Editing: Rainer Kiss, Thomas Muehlbauer

We hereby confirm that each of us contributed to the aforementioned publication as indicated above and acknowledge that the main part of work was carried out by Simon Schedler.

Prof. Dr. Rainer Beurskens (formerly Kiss)

Prof. Dr. Thomas Muehlbauer

9.2 Author Contributions to STUDY II: *"Relationships between types of balance performance in healthy individuals: role of age"*

Conceptualization: Simon Schedler, Thomas Muehlbauer

Data Curation: Simon Schedler, Elisa Abeck

Formal Analysis: Simon Schedler

Methodology: Simon Schedler

Writing – Original Draft: Simon Schedler

Writing – Review & Editing: Thomas Muehlbauer, Elisa Abeck

We hereby confirm that each of us contributed to the aforementioned publication as indicated above and acknowledge that the main part of work was carried out by Simon Schedler.

Muehlbauer Elisa Abeck

Prof. Dr. Thomas Muehlbauer Elisa Abeck

9.3 Author Contributions to STUDY III: *“Effects of Balance Training on Balance Performance in Youth: Are There Age Differences?”*

Conceptualization: Simon Schedler, Thomas Muehlbauer

Data Curation: Simon Schedler, Katharina Brock, Fabian Fleischhauer

Formal Analysis: Simon Schedler

Methodology: Simon Schedler

Writing – Original Draft: Simon Schedler

Writing – Review & Editing: Thomas Muehlbauer, Rainer Kiss, Katharina Brock, Fabian Fleischhauer

We hereby confirm that each of us contributed to the aforementioned publication as indicated above and acknowledge that the main part of work was carried out by Simon Schedler.

Prof. Dr. Thomas Muehlbauer | Prof. Dr. Rainer Beurskens (formerly Kiss)

Katharina Brock * | Fabian Fleischhauer

* Note: Due to the long time period between the publication of STUDY III and the finalisation of this doctoral dissertation, I was unable to contact Mrs. Brock. However, she approved the final manuscript naming me as being the first and corresponding author during the submission and revision process.

9.4 Author Contributions to STUDY IV: *“Effect of practice on learning to maintain balance under dynamic conditions in children: Are there sex differences?”*

Conceptualization: Simon Schedler, Thomas Muehlbauer

Data Curation: Simon Schedler, Dennis Brueckner

Formal Analysis: Simon Schedler, Rainer Kiss, Thomas Muehlbauer

Methodology: Simon Schedler, Dennis Brueckner

Writing – Original Draft: Simon Schedler, Thomas Muehlbauer

Writing – Review & Editing: Thomas Muehlbauer, Rainer Kiss, Dennis Brueckner

We hereby confirm that each of us contributed to the aforementioned publication as indicated above and acknowledge that the main part of work was carried out by Simon Schedler.

Prof. Dr. Thomas Muehlbauer

Prof. Dr. Rainer Beurskens (formerly Kiss)

Dennis Brueckner

Declarations (Erklärungen)

1

Hiermit erkläre ich, dass die eingereichte Dissertation aus keinem Projekt entstanden ist, an dem mehrere Personen mitgewirkt haben.

2

Hiermit erkläre ich, dass ich die eingereichte Dissertation zum Thema „The Influence of Age and Sex on Balance Performance and Balance Trainability in Youth“ selbständig verfasst habe.

3

Hiermit erkläre ich, dass diesem Promotionsverfahren keine endgültig gescheiterten Promotionsversuche in diesem Fach oder in einem anderen Fach vorausgegangen sind.

4

Hiermit erkläre ich, dass ich die eingereichte Dissertation selbständig verfasst und keine anderen als die angegebenen Hilfsmittel benutzt und alle wörtlich oder inhaltlich übernommenen Stellen als solche gekennzeichnet habe.

5

Hiermit erkläre ich, dass ich die eingereichte Dissertation nur in diesem Promotionsverfahren eingereicht habe.

Hamm, 16.03.2022, Unterschrift