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THE ROLE OF SURFACE CONDITION IN ATHLETIC PERFORMANCE

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Affidavits according to doctoral degree regulations (§ 4 (2), sentences No. 4 and 7) of the Faculty of Human Sciences, University of Potsdam:

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

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Abstract

During the last two decades, instability training devices have become a popular means in athletic training and rehabilitation of mimicking unstable surfaces during movements like vertical jumps. Of note, under unstable conditions, trunk muscles seem to have a stabilizing function during exercise to facilitate the transfer of torques and angular momentum between the lower and upper extremities. The present thesis addresses the acute effects of surface instability on performance during jump-landing tasks. Additionally, the long-term effects (i.e., training) of surface instability were examined with a focus on the role of the trunk in athletic performance/physical fitness.

Healthy adolescent, and young adult subjects participated in three cross-sectional and one longitudinal study, respectively. Performance in jump-landing tasks on stable and unstable surfaces was assessed by means of a ground reaction force plate. Trunk muscle strength (TMS) was determined using an isokinetic device or the Bourban TMS test. Physical fitness was quantified by standing long jump, sprint, stand-and-reach, jumping sideways, Emery balance, and Y balance test on stable surfaces. In addition, activity of selected trunk and leg muscles and lower limb kinematics were recorded during jump-landing tasks.

When performing jump-landing tasks on unstable compared to stable surfaces, jump performance and leg muscle activity were significantly lower. Moreover, significantly smaller knee flexion angles and higher knee valgus angles were observed when jumping and landing on unstable compared to stable conditions and in women compared to men. Significant but small associations were found between behavioral and neuromuscular data, irrespective of surface condition. Core strength training on stable as well as on unstable surfaces significantly improved TMS, balance and coordination.

The findings of the present thesis imply that stable rather than unstable surfaces provide sufficient training stimuli during jump exercises (i.e., plyometrics). Additionally, knee motion strategy during plyometrics appears to be modified by surface instability and sex. Of note, irrespective of surface condition, trunk muscles only play a minor role for leg muscle performance/activity during jump exercises. Moreover, when implemented in strength training programs (i.e., core strength training), there is no advantage in using instability training devices compared to stable surfaces in terms of enhancement of athletic performance.

Zusammenfassung

Instabile Trainingsgeräte sind etablierte Bestandteile im sportlichen Training und in der Rehabilitation, um instabile Untergründe während verschiedener alltags- und sportartspezifischer Bewegungen zu simulieren. Dabei scheint der Rumpfmuskulatur insbesondere unter instabilen Bedingungen eine wichtige Rolle zur Stabilisierung zu zukommen. Die vorliegende Arbeit widmet sich den Akuteffekten von Untergrundinstabilität auf die Leistung bei Sprüngen und Landungen. Zudem wurden Langzeiteffekte von Untergrundinstabilität auf die Bedeutung des Rumpfes für die sportliche/sportmotorische Leistung untersucht.

Gesunde Jugendliche und junge Erwachsene nahmen an drei Quer- bzw. einer Längsschnittstudie teil. Die Leistung der Sprung-Lande-Aufgaben auf stabilen und instabilen Untergründen wurde mittels Kraftmessplatte erfasst. Die Rumpfkraft wurde mit einem Isokineten oder dem Bourban-Rumpfkraft-Test gemessen. Die Ermittlung sportmotorischer Leistungen erfolgte durch Standweitsprung-, Sprint-, Rumvorbeuge-, Seitsprung-, Emery- und Y-Balance-Test auf stabilen Untergründen. Zudem wurde die Aktivität ausgewählter Rumpf- und Beinmuskeln und Beinkinematik während der Sprung-Lande-Aufgaben erfasst.

Sprung-Lande-Aufgaben auf instabilen im Vergleich zu stabilen Unterlagen führten zu signifikant geringeren Sprungleistungen und Beinmuskelaktivitäten. Dabei wurden die Kniegelenke unter instabilen im Vergleich zu stabilen Bedingungen stärker extendiert und valgisiert. Dies gilt auch für Frauen im Vergleich zu Männern während des Springens und Landens. Zusammenhänge zwischen den Verhaltens- und neuromuskulären Daten unabhängig vom Untergrund sind als gering einzuschätzen sind. Ein Rumpfkrafttraining auf stabilen sowie auf instabilen Untergründen verbesserte die Rumpfkraft, das Gleichgewicht und die Koordination.

Zusammenfassend zeigen die Ergebnisse, dass stabile gegenüber instabilen Unterlagen bessere Voraussetzungen bei Sprungübungen zur Steigerung der Sprungleistung im Training schaffen. Zudem scheint die biomechanische Kontrollstrategie des Kniegelenks bei Sprüngen durch den Untergrund und das Geschlecht modifiziert. Dabei ist zu erwähnen, dass für den Leistungsvollzug der unteren Extremitäten beim Springen der Rumpf unabhängig von den Untergrundbedingungen nur eine kleine Rolle zu spielen scheint. Darüber hinaus zeigen instabile gegenüber stabilen Untergründen in einem Rumpfkrafttraining keinen Vorteil hinsichtlich der Steigerung sportlicher Leistungen.

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Abbreviations

ACL	anterior cruciate ligament
BF	m. biceps femoris
COM	center of mass
CoV	coefficient of variation
CS	composite score
CSTS	core strength training performed on stable surfaces
CSTU	core strength training performed on unstable surfaces
DJ	drop jump
EMG	electromyographic
ES	m. erector spinae
GM	m. gastrocnemius medialis
GRF	ground reaction force
ICC	intraclass correlation coefficient
iEMG	integrated EMG
MAV	mean average voltage
MVC	maximum voluntary contraction
PIT	peak isokinetic torque
RA	m. rectus abdominis
SD	standard deviation
SLR	short latency response
TA	m. tibialis anterior
VM	m. vastus medialis

1. Introduction

In sports and everyday life, adequate levels of physical fitness (e.g., strength, power, endurance) are necessary in order to successfully perform sport-specific tasks and activities of daily living. For instance, in team sports, different types of activities are performed throughout ball games such as handball or soccer, ranging from low-intensity running to bouts of maximal sprint and power output. During competition, athletes need to outperform their opponents, which requires high levels of aerobic capacity, speed and agility, as well as maximal and explosive strength (Stølen et al. 2005, Ziv & Lidor 2010). Further, in terms of activities of day-to-day life, training-related gains in performance measures, such as maximal and explosive strength, may also help to decrease the risk of sustaining injuries or falls, particularly in youth and older adults (Granacher et al. 2011). It appears that explosive strength of the leg muscles and movement tasks like good vertical or horizontal jump performance are essential elements of athletic performance and training (i.e., plyometric training) (Bobbert 1990, Gollhofer & Bruhn 2003, Ziv & Lidor 2010).

It has to be noted that during training and competition, sport-specific performance (e.g., on jump-landing tasks) often occur under relatively unstable conditions (e.g., landing on uneven natural turf in soccer after a header, landing on compliant mats in gymnastics, jumping on different playground surfaces). In this regard, it has been recommended that training attempt to closely mimic the demands of the respective sport-specific or everyday activity in order to adhere to the principle of training specificity (Behm & Sale 1993). According to this principle, training under unstable conditions may provide a sufficient level of instability that is also present during the performance of sport-specific tasks and everyday activities, providing a more effective transfer of training adaptations as compared to training under stable conditions (Behm & Anderson 2006). Thus, unstable devices such as Swiss balls, BOSU (both sides up) balls, wobble boards or balance pads have become popular instruments in recent decades used in athletic training and rehabilitation with the goal of mimicking surface instability during training, competition, and everyday life. However, it has to be noted that surface condition is also discussed as a factor having an impact on injury risk during lower limb exercises (Orchard 2002). Therefore, it is important to know whether stimuli during jump-landing tasks on unstable surfaces are both sufficiently unstable and safe before implementing exercises on unstable devices in training (e.g., plyometric training programs).

Particularly in the lay literature, the term “core” (or torso or trunk) has recently gained a lot of attention in terms of its role in supporting athletic performance. According to Akuthota et al. (2008), the core refers to a muscular box consisting of the abdominals in the front, paraspinals and gluteals in the back, the diaphragm as the roof, and the pelvic floor and hip girdle muscles as the bottom. Functionally, these muscles are centrally located in almost all kinetic chains and important for stabilizing the spine and pelvis, providing proximal stability for distal mobility and function of the limbs (Kibler et al. 2006). In terms of maximal jumping, Blache and Monteil (2014) recently showed in a simulation model that vertical jump height was significantly lower if activity of the spinal erector muscle was excluded from the model. Thus, it can be argued that there is an association between performance measures of the trunk muscles and lower limb muscles. In particular, it will be interesting to coaches and therapists whether this relationship is more pronounced under unstable conditions. Intuitively, it is suggested that unstable surfaces require greater stability of the spine. Given that a stable core is pivotal to upper and lower limb function, it seems even plausible to argue that training programs with core strengthening exercises may have the potential to improve variables of athletic performance. Specifically, strength training programs using instability training devices were discussed in terms of enhancing core strength and thus athletic performance output (Behm et al. 2010b, Behm & Colado-Sanchez 2013). In this regard, practitioners may be interested in whether integrating unstable elements in specific core strength training programs could provide an extra stimulus for strength promotion, resulting in superior performance enhancements compared to core strength training under stable conditions.

Thus, the main objective of the present thesis is to evaluate the role of unstable surface conditions frequently used during athletic training and rehabilitation on measures of athletic performance (e.g., strength, speed, power). This cumulative thesis comprises three cross-sectional studies and one longitudinal study which were recently published in peer-reviewed journals and addressed the acute effects of surface instability on performance during jump-landing tasks. Additionally, long-term effects of surface instability on the importance of the trunk for athletic performance were examined.

2. Literature review

2.1 Biomechanics of jumping and landing

2.1.1 Functional aspects of jump-landing tasks

In order to describe how muscular force production interacts with external forces (e.g., gravity, mass of sports objects), muscle function during exercises has traditionally been characterized by isometric, concentric (i.e., shortening) or eccentric (i.e., lengthening) actions (Knuttgen & Komi 2003). However, the natural forms of muscle function such as jump-landing tasks are often characterized by large transient reaction forces (Santello 2005). During these movements, a combination of muscle actions is utilized, rather than one single type of isolated action (Komi 2003).

For instance, when performing jumping tasks, the leg extensor muscles acting around the knee and/or ankle joint are eccentrically preloaded (stretched) during a loading or impact phase due to external force (i.e. gravity). Immediately following stretch, these muscles shorten concentrically during a push-off or take-off phase (Gollhofer & Bruhn 2003, Komi 2003). Additionally, the preactivation of agonistic extensor muscles prior to mechanical loading has been emphasized as providing a powerful and efficient transfer of energy from eccentric to concentric action. The combination of preactivation during a pre-landing period and eccentric as well as concentric muscle actions during a ground contact period constitutes the model known as the "*stretch-shortening cycle*" (SSC) (Komi & Gollhofer 1997, Gollhofer & Bruhn 2003, Komi 2003).

Functionally, the purpose of the SSC is to enhance force and power output during the final concentric action, compared to conditions in which isolated concentric actions are used (Komi & Gollhofer 1997, Komi 2003). For instance, some decades ago, Cavagna et al. (1968) investigated the ratio of physical work during concentric actions immediately following eccentric actions relative to work during concentric actions starting from isometric actions in human elbow flexor muscles, as well as in isolated animal muscles. The authors reported that ratio values always appeared to be larger than 1, increasing up to 1.8 (depending on the velocity of stretching/ lengthening). Later, these findings on SSC-induced performance potentiation were confirmed during more complex exercises such as walking, running and vertical jumping (Asmussen & Bonde-Petersen 1974, Komi & Bosco 1978, Bosco et al. 1982, Bobbert et al. 1996, Bosco et al. 1997). In terms of jumping, particularly the drop jump exercise has been established to study the SSC in lower limbs, which requires athletes to quickly rebound as high as possible following a drop down from a specific height. Notably, for optimal force potentiation it seems to be inevitable that the transition from eccentric to concentric action is fast, since longer delay periods significantly reduce potentiation effects (Komi 2003, Gollhofer & Bruhn 2003). Further, several mechanisms such as storage of elastic energy (Asmussen & Bonde-Petersen 1974, Komi & Bosco 1978, Bosco et al. 1982), mechanical efficiency (Bosco et al. 1997), time for force generation prior to concentric action (Bobbert et al. 1996) and neuromuscular preactivation and stretch reflexes (Bosco et al. 1982, Avela et al. 1996, Komi & Gollhofer 1997, Trimble et al. 2000) that potentially affect performance enhancement in SSC movement tasks have been discussed in the literature.

Similar to the SSC model, landing tasks can be characterized by pre-landing and ground contact periods as well (Santello 2005, Liebermann 2008). However, due to the nature of the landing, there is an amortization of ground reaction forces rather than an efficient transfer of energy from eccentric to concentric action during landing compared to jumping. In fact, the ground reaction force experienced throughout impact has to be spread out over time (Dufek & Bates 1990). For instance, this concept is frequently used by judo athletes when rolling laterally after falling in order to decrease pressure and prolong ground contact time (Groen et al. 2007). In this regard, Liebermann (Liebermann 2008) argued that during the pre-landing period, subjects follow a plan of action based on a temporal framework defined by the instant of release and the instant of touch-down. During the ground contact period, subjects' motor responses are assumed to follow either the law of biomechanics or anticipatory motor strategies (depending on the magnitude of impact forces) (Liebermann 2008).

The main goal of proper landing performance is the prevention of potential injuries, particularly of the lower limbs (Arendt et al. 1999, Santello 2005, Liebermann 2008). In support of this notion, Olsen et al. (2004) and Faunø and colleagues (2006) reported that landing and decelerating movement patterns accounted for 25 to 30 % of severe knee injuries (i.e., rupture of anterior cruciate ligament [ACL]) in handball and soccer athletes, respectively. In basketball players, even 59 % of ACL injuries were identified as occurring during jump-landing tasks (Krosshaug et al. 2007). Of note, these injuries can predominately be described as non-contact injuries. Thus, the functional movement pattern of jumping can be considered highly important, particularly from a health-related perspective. Regarding mechanisms potentially affecting landing performance, several aspects have been discussed that can be summarized as follows: reflexive actions following release, neuromuscular preactivation, cognitive input, anticipatory adjustments, stretch reflex mechanisms, and multi-joint interactions (Santello 2005, Liebermann 2008).

2.1.2 Neuromuscular control of jump-landing tasks

During jumping and landing, the activation levels of muscles involved in performance have to be modulated properly in order to control for specific demands (e.g., stretching load, surface condition, visual feedback) during ground contact. In this regard, *preactivation* and *stretch reflex mechanisms* are key features of neuromuscular control strategy.

2.1.2.1 Preactivation

During jump-landing tasks, it appears that some of the lower limb muscles are already activated before ground contact. In fact, it was observed that electromyographic (EMG) activity of leg muscles started at 40-140 ms prior to the instant of touch-down (Greenwood & Hopkins 1976, Gehring et al. 2009, Fleischmann et al. 2010). Notably, the onset of activation during jumping and landing is specific for the muscle and its functional role in the kinetic chain. More precisely, in the distal shank muscles, which are the first ones exposed to external loading during the ground contact period, preactivation starts about 50 ms earlier compared to thigh muscles (Gehring et al. 2009, Fleischmann et al. 2010). There is general consent in the scientific literature that neuromuscular preactivation contributes to stiffness regulation of the respective joints in preparation for forthcoming impact loads during ground contact (Gollhofer et al. 1984, Avela et al. 1996, Horita et al. 2002). Basically, this neuromuscular control strategy results in modulating the spring-like behavior of the muscle-tendon unit, thus allowing for the absorption of the body’s momentum over a wide range of time courses and magnitudes across movement tasks (e.g., from landing to hopping, jumping and running) (Santello 2005).

From a mechanistic point of view, Melvill Jones and Watt (1971) suggested in earlier days that muscle activation prior to ground contact is pre-programmed and controlled by higher motor centers. The authors stated that the correct timing and sequence of muscle contractions have been learned over time by previous experience (Melvill Jones & Watt 1971). In fact, several studies showed that the duration and/or level of neuromuscular preactivation is related to expected impact loads by modulating dropping/falling height or jumping distance (Dyhre-Poulsen et al. 1991, Avela et al. 1996, Santello & McDonagh 1998, Fleischmann et al. 2010, Hoffrén et al. 2011). Further, Avela et al. (1996) showed that the duration and level of preactivation in drop jump exercises is modulated by changes in body mass and gravity as well. Thus, the authors concluded that control mechanisms may also depend on proprioceptive, vestibular and visual inputs during performance (Avela et al. 1996). Interestingly, visual input of the environment prior to landing appears to be more important than online information (Liebermann & Goodman 2007).

2.1.2.2 Stretch reflexes

The occurrence of reflex activity due to stretching is a well-known and important factor contributing to performance during ground contact periods of SSC jumping (Komi 2003) and, to some extent, landing tasks (Santello 2005). Specifically, it was argued that stretch reflexes in addition to voluntary muscle activation may increase muscle stiffness of lower limb muscles (e.g., m. vastus medialis, m. soleus) and thus enhance SSC performance output (Gollhofer et al. 1984, Avela et al. 1996, Horita et al. 1996, Komi & Gollhofer 1997, Nicol & Komi 1998). Melvill Jones and Watt (1971) were the first to note that stretch reflex-induced activation may contribute to performance during hopping at preferred frequencies. In fact, Hoffer and Andreassen (1981) demonstrated in cats that muscle stiffness is greater for the same operating force when reflexes are intact in agonistic muscles compared to areflexive muscles. In another study, Nicol and Komi (1998) investigated the effect of reflex contribution to stiffness and force potentiation of Achilles tendon force production in humans during passive dorsiflexion stretches. The authors found stretch-induced reflex EMG activity in high-velocity stretches that clearly enhanced Achilles tendon force by 200-500 % compared to low-velocity stretches without EMG reflex potential (Nicol & Komi 1998). Thus, stretch reflexes may already constitute a net contribution to muscle stiffness during the eccentric part of SSC movements (Komi 2003). In this regard, several time intervals were defined as representing specific stretch responses (Taube et al. 2008): short-latency response (SLR), medium latency response, late-latency response (1 and 2). Notably, neuromuscular control of early reflex responses during SSC movements is predominantly modulated on the spinal level, whereas late responses are predominantly controlled by supraspinal centers (Taube et al. 2008). In support of this finding, SLR activity during drop jumps was enhanced when the stretching load increased by increasing the drop height (Komi & Gollhofer 1997, Leukel et al. 2008). However, when performing jumps from excessive heights, the SLR component becomes less distinct, indicating preventive strategies of supraspinal neuromuscular control (Leukel et al. 2008).

In terms of landing tasks, Melvill Jones and Watt (1971) argued that neuromuscular activity during ground contact is pre-programmed and inaccessible to reflex activity. In studies of Dyhre-Poulsen et al. (1991) and Leukel and colleagues (2008), spinal excitability was assessed during landing maneuvers using the H (Hoffmann) reflex technique. It was stated that stretch reflexes may be inhibited by central motor programs as measured by reduced H reflex responses during ground contact periods (Dyhre-Poulsen et al. 1991, Leukel et al. 2008). However, there is still controversy in the literature over whether muscle activity during ground contact is a reflex response to stretch or a programmed response (for review, see Santello 2005). Overall, the scientific literature suggests a possible contribution of reflex mechanisms to a more central control of muscle force production during landing with rapid joint rotations following the instant of ground contact (Santello 2005).

2.2 Studies on surface instability and athletic performance

In several types of sports, performance frequently involves situations in which athletes are challenged to act under unstable conditions. Surface properties and/or opponent contact, particularly in team sports, can demand specific adaptations in order to compensate for perturbations and maintain performance output at a high level. This should be considered by coaches and practitioners implementing training programs. In fact, according to the concept of training specificity (Behm & Sale 1993), it was postulated that training must comply with the demands of the respective sport-specific or even everyday activity (Behm & Anderson 2006, Behm et al. 2010b). In this regard, a variety of instability training devices have successfully been introduced to the training and fitness market in recent decades to mimic unstable surface conditions in athletic training and rehabilitation. Thus, investigating the effect of instability training devices on different performance measures (e.g., athletic/physical, neuromuscular, or kinematic/kinetic performance) has become a popular field of scientific research since the early 2000s.

2.2.1 Kinetic and kinematic changes with surface instability

There are a multitude of studies investigating how performance measures such as force and power output are affected when applying instability training devices to upper and lower limb strengthening exercises. In one of the first experiments that addressed this specific question, the research group of Behm and colleagues (2002) examined isometric maximum voluntary contractions (MVC) of unilateral knee extension and plantar flexion actions in physically active male subjects. During exercise, participants were seated either on a bench/chair (i.e., stable condition) or on a Swiss ball (i.e., unstable condition). The authors found that isometric MVC was significantly lower in leg extension (70 %) and plantar flexion (20 %) when performed on a Swiss ball compared to the stable condition (Behm et al. 2002). These findings are not only confined to single-joint movements, but were also reported for multi-joint movements (e.g., squats, chest press) (Anderson & Behm 2004, McBride et al. 2006, Zemková et al. 2012, Saeterbakken & Fimland 2013a, 2013b). For instance, athletic male college students were asked to perform maximal isometric squats on a force plate during stable conditions and on inflatable balance discs on top of the force plate during unstable conditions (McBride et al. 2006). On the balance disc, peak force and the rate of force development decreased by 46 % and 41 %, respectively, as compared to the firm force plate condition. Further, in terms of upper limb exercises, resistance-trained male participants executed maximal isometric chest press either on a bench or on a Swiss ball (Anderson & Behm 2004). In this study, force production under unstable conditions was at 60 %, relative to stable conditions. Additionally, when upper (i.e., bench press) and lower limb exercises (i.e., squats) were performed dynamically on unstable surfaces (i.e., Swiss ball, BOSU ball), significantly lower power output (7-17 %) was observed compared to stable surfaces (i.e., bench, floor) in physical education students (Zemková et al. 2012). Thus, it can be concluded that force and power output is impaired when performing “classical” strengthening exercises, such as squats and bench press, under unstable compared to stable conditions. In fact, it has been shown that force impairment is enhanced with increasing levels of surface instability during lower and upper limb exercises (Saeterbakken & Fimland 2013a, 2013b).

Interestingly, in terms of SSC-like movements, studies partly reveal contradictory findings regarding the effect of surface condition on performance output (Bosco et al. 1997, Kerdok et al. 2002, Arampatzis et al. 2004). For instance, Kerdok et al. (2002) reported that running economy was enhanced by 12 % in healthy male subjects when surface stiffness decreased while running on a force-plate-fitted treadmill. Similarly, mechanical work in well-trained sprinters has been found to be significantly more efficient (2 %) during repeated hopping on a compliant surface compared to a hard surface (Bosco et al. 1997). Lastly, Arampatzis et al. (2004) observed an advantage for the compliant compared to the hard surface (7 %) during maximal jumping (i.e., drop jumps) in female varsity gymnasts due to a higher ratio of positive to negative mechanical work accomplished by the subject during the ground contact phase.

From a health-related perspective, surface condition has been discussed as a factor contributing to knee injury risk during lower limb (SSC) exercises (Orchard 2002). In this regard, it has frequently been demonstrated that surface conditions may affect the biomechanical parameters of lower extremities while running (Ferris et al. 1998, Kerdok et al. 2002, Derrick 2004), jumping (Ferris et al. 1998, Moritz & Farley 2003, Arampatzis et al. 2004), and landing (McNitt-Gray et al. 1994). Notably, earlier studies were able to elucidate different biomechanical factors, such as excessive knee abduction (valgus) (Krosshaug et al. 2007, Myer et al. 2012) and insufficient knee flexion (Derrick 2004, Chappell et al. 2007, Myer et al. 2012), that are most likely responsible for an increased risk of ACL injury during jump-landing tasks, particularly in females. In terms of instability-related adaptations in lower limb biomechanics, Kerdok et al. (2002) reported significantly lower maximum knee flexion angles with instability in healthy male subjects when running on surfaces with different stiffness levels. In addition, McNitt-Gray et al. (1994) investigated landing strategies in gymnasts on gymnastic mats of different stiffness levels. Findings revealed that knee flexion angles were significantly lower on compliant versus hard surfaces. However, it remains unresolved whether unstable/foam surfaces produce similar effects during maximal plyometric exercises (i.e., drop jumps) as those reported for running and submaximal jumping (i.e., hopping) on surfaces of different stiffness levels (Ferris & Farley 1997, Ferris et al. 1998, Kerdok et al. 2002, Moritz & Farley 2003, Derrick 2004) and landing on gymnastic mats (McNitt-Gray et al. 1994).

2.2.2 Neuromuscular changes with surface instability

In addition to mechanical output variables, several studies have generated information on electrophysiological measures during performance on instability training devices compared to stable surface conditions. However, the body of literature reveals inconsistent findings (Behm et al. 2002, Anderson & Behm 2005, McBride et al. 2006, McBride et al. 2010, Bressel et al. 2009, Saeterbakken & Fimland 2013a, 2013b). For instance, Behm et al. (2002) reported a decrease in quadriceps activity (11 %) but an increase in hamstring activity (29 %) during unilateral isometric knee extension MVCs. Further, lower muscle activation in quadriceps muscles (34-37 %) without changes in hamstring muscle activity has been observed during the performance of isometric squats on unstable surfaces (McBride et al. 2006). In a study by Saeterbakken and Fimland (2013b), neuromuscular performance of lower limb muscles in healthy male subjects was investigated during isometric squats on stable (i.e., floor) and unstable surfaces (i.e., power board, BOSU ball, balance cone). A decrease in leg muscle activity was found in one muscle only (i.e., m. rectus femoris) during isometric squats under unstable conditions (15-25 %), whereas activity in all other analyzed leg muscles remained unchanged. Lastly, in terms of dynamic exercises (i.e., squats, chest press), increases (Anderson & Behm 2005) as well as decreases (McBride et al. 2010, Saeterbakken & Fimland 2013a) have been reported for lower and upper limb muscle activity, respectively.

Interestingly, researchers investigated not only the muscle activity of prime movers (i.e., limb muscles), but also that of trunk muscles when performing upper or lower limb exercises with surface instability. In this regard, it was shown that the activity of trunk muscles (i.e., abdominal muscles, spinal erector muscles) was higher in healthy young men (25-51 %) when dynamic squats were performed on balance discs compared to the Smith machine (Anderson & Behm 2005). These results were partly confirmed for dynamic upper limb exercises (i.e., chest press) in healthy resistance-trained males (Saeterbakken & Fimland 2013a). In their study, rectus abdominis activity during exercise on a Swiss ball was 44 % higher compared to exercise on a stable bench, whereas no differences were observed for spinal erector and external oblique muscles. It has to be noted, though, that there are also contrary study findings suggesting that core muscle activity does not change at all when investigating different surface conditions during both upper and lower limb exercises (Anderson & Behm 2004, McBride et al. 2010, Saeterbakken & Fimland 2013b).

2.3 Instability for training the core muscles

The findings on potentially higher trunk muscle activity when performing actions on unstable surfaces indicate the importance of a stable core for athletic function. Specifically, it has been proposed that trunk muscles are part of a centrally located muscular box (i.e., core) that stabilizes the spine, thereby facilitating the transfer of torques and angular momentum between the lower and upper extremities during sports performance, fitness activities, and even activities of daily living (Akuthota et al. 2008, Behm et al. 2010b). According to Kibler et al. (2006), the core provides proximal stability for distal mobility. Given that, Behm and Anderson (2006) argued that similar or higher levels of trunk muscle activation accompanied by lower levels of force/power output with instability indicate that the motive forces of the muscles (i.e., their ability to apply external force) were transferred into greater stabilizing forces. Consequently, it seems reasonable to assume that increased core stability/trunk muscle strength can improve athletic performance. In fact, data from cross-sectional studies indicate significant associations between measures of trunk muscle strength and athletic performance (e.g., agility, jump, or sprint performance) (Nesser et al. 2008, Wells et al. 2009, McKean & Burkett 2010, Okada et al. 2011, Shinkle et al. 2012). For instance, Nesser et al. (2008) showed that significant correlation coefficients between the variables of isometric frontal/ dorsal/ lateral trunk muscle endurance and vertical jump performance ranged from r = .40 to r = .54 in male Division I strength and power athletes. Moreover, in a longitudinal study design, the impact of a 6-week core strengthening program was investigated in healthy untrained school-aged children (Allen et al. 2014). As a result, the authors found significant performance enhancements (17-45 %) in different trunk muscle endurance tests (i.e., Parallel Roman Chair Dynamic Back Extension, Prone Plank, Lateral Plank, Dynamic Curl-Up, Static Curl-up). Furthermore, in a randomized controlled trial, significant improvements in unilateral hip muscle strength (41 %) and jump performance (5-7 %) were found in adolescent soccer players following 6 months of combined core stability/strength training and regular soccer training compared to soccer training alone (Hoshikawa et al. 2013). In light of these findings, it seems plausible to argue that core strengthening may have the potential to improve athletic performance.

Additionally, findings on neuromuscular changes with surface instability during upper and lower limb exercises indicate that the integration of unstable surfaces during strength training could provide extra stimuli to increase trunk muscle strength and thus enhance athletic performance to a larger extent than that of stable surfaces. Specifically, when performing core strengthening exercises on unstable surfaces (e.g., BOSU ball, Swiss ball, suspension device), higher trunk muscle activity has been observed compared to stable surfaces (Vera-Garcia et al. 2000, Imai et al. 2010, Sundstrup et al. 2012, Snarr & Esco 2014). In one study, Vera-Garcia and colleagues (2000) reported that muscle activation levels in the rectus abdominis and external oblique muscles of healthy young men were higher during crunches on a Swiss ball (15 and 5 % of MVC, respectively) compared to a stable bench. Further, Snarr and Esco (2014) extended these results by showing that muscle activity in physically active men and women was higher in rectus abdominis (19-55 % of MVC), external oblique (17-43 % of MVC), and spinal erector muscles (3-11 % of MVC) when prone planks were performed under several unstable conditions (i.e., planks with elbow or feet on a Swiss ball or suspension device) compared to traditional prone planks on an exercise mat. In a recent longitudinal approach, Granacher et al. (2013) conducted a 9-week progressive core strength training on unstable surfaces in community-dwelling older adults. Compared to a passive control group, the intervention group significantly improved their measures of trunk muscle strength (21-53 %), spinal mobility (11 %), functional mobility (4 %), and dynamic balance (9-31 %). In this regard, it has been propagated that the integration of unstable surfaces in (core) strength training programs could provide extra stimuli to improve performance in a superior way compared to stable surfaces (Behm et al. 2010b).

3. Research objectives

In summary, the previous paragraphs have demonstrated that several studies examined how surface conditions affect performance when instability training devices are implemented in traditional strengthening exercises (e.g., squats, bench press, curl ups). Further, in terms of strength training under unstable conditions, it has been shown that studies particularly highlighted the importance of trunk muscle strength for athletic performance. However, there are still gaps in the literature that need to be elucidated and that appear to be of special interest for coaches and practitioners.

Regarding the effects of surface instability on athletic performance, it is unknown how unstable devices affect performance during SSC movements. In fact, previous studies investigated the effects of surface instability on SSC movements, such as jump-landing tasks using stable/firm surfaces of different stiffness levels. Jump-landing tasks are essential components of athletic performance and are associated with an increased risk of non-contact injuries of the lower limbs, in particular for females. Therefore, it is crucial to know the acute effects on biomechanics during jumping and landing in physically active males and females when instability training devices are used during jump exercises. More precisely, this thesis is going to address the question of whether neuromuscular as well as kinetic and kinematic variables during jump-landing tasks under unstable conditions in males and females are different from those obtained under stable conditions.

In addition, there is still a gap in our knowledge with regards to the role of the core during the performance of exercises on unstable surfaces, such as jumping on both stable and unstable surfaces. For instance, studies applied trunk muscle endurance tests comprising submaximal isometric muscle actions in order to evaluate trunk muscle strength. These tests may not be adequate to illustrate the importance of trunk muscle strength for athletic performance, because many sports-related movements (e.g., jumping) require maximal dynamic force production. Further, in addition to this behavioral approach, assessing neuromuscular data could add complementary and in-depth information on the role of the trunk during jump tasks on different surfaces. Yet, it remains unknown whether maximal dynamic trunk muscle strength is associated with jump performance under stable and unstable conditions and whether this association may be reflected in the relationship between the neuromuscular performance of trunk and leg muscles. In particular, it will be interesting to practitioners whether these relationships are more pronounced under unstable conditions when greater stabilizing forces are required.

Lastly, core strength training has been shown to be effective in improving measures of trunk muscle strength and athletic/physical performance, particularly in youth and the elderly. Given the supposed role of instability to train the core muscles, (core) strength training using unstable surfaces/devices could provide extra stimuli to improve performance in a superior way as compared to stable conditions (Behm et al. 2010b). Notably, strengthening programs implementing instability training devices were propagated for performance enhancement and musculoskeletal health in youth (Behm & Colado-Sanchez 2013). Therefore, it will be interesting to know whether the integration of unstable elements in specific core strength training programs (CSTU) could provide an extra stimulus for strength promotion in youth, resulting in superior performance enhancements compared to core strength training under stable conditions (CSTS).

Based on these questions, the research objectives of this thesis concerning the role of instability in athletic performance can be summarized as follows:

1. The first objective was to investigate the sex-specific effects of surface instability on biomechanical performance measures (i.e., EMG activity, kinetics, kinematics) during jump-landing tasks (i.e., drop jumps, landings). It was hypothesized that EMG activity decreases during drop jumps and landings on unstable versus stable surfaces. Additionally, it was expected that lower limb kinematics are sex-specifically modulated on unstable versus stable surfaces (study 1 and study 2).

2. The second objective was to examine the associations between trunk muscle strength, jump performance, and lower limb kinematics, as well as between trunk and leg muscle activity during drop jumps on stable and unstable surfaces. The hypothesis was that significant correlations can be observed between trunk muscle

strength, drop jump performance, and lower limb kinematics, as well as between trunk and leg muscle activity, which are more pronounced on unstable versus stable surfaces (study 3).

3. The third objective was to investigate the effects of CSTU versus CSTS on health- and skill-related components of physical fitness in youth. It was hypothesized that participants performing CSTU compared to CSTS will show larger improvements in physical fitness tests (e.g., strength, speed, balance) following core strength training (study 4).

Table 1: Characteristics of the studies included in the present thesis.

Study	Journal	Design	Participants	Measures	Chapter
1	Eur J Appl Physiol (peer-reviewed)	cross-sectional	M (n=14), F (n=13); mean age: 23±3 years	jump performance, EMG activity	4.1
2	Int J Sports Med (peer-reviewed)	cross-sectional	M (n=14), F (n=14); mean age: 23±3 years	jump performance, kinetics, frontal and sagittal plane kinematics	4.2
3	Eur J Appl Physiol (peer-reviewed)	cross-sectional	M (n=14), F (n=15); mean age: 23±3 years	jump performance, EMG activity, frontal plane kinematics	4.3
4	BMC Sports Sci Med Rehabil (peer-reviewed)	randomized controlled trial	M (n=13), F (n=14); CSTU (n=14), CSTS (n=13); mean age: 14±1 years	trunk muscle strength, physical performance	4.4

CSTS = core strength training performed on stable surfaces, CSTU = core strength training performed on unstable surfaces, F = female, M = male

4. Studies

4.1 Study 1

EFFECTS OF SURFACE INSTABILITY ON NEUROMUSCULAR PERFORMANCE DURING DROP JUMPS AND LANDINGS

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Reference

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4.1.1 Abstract

The purpose of this study was to investigate the effects of surface instability on measures of performance and activity of leg and trunk muscles during drop jumps and landings. Drop jumps and landings were assessed on a force plate under stable and unstable (balance pad on top of the force plate) conditions. Performance measures (contact time, jump height, peak ground reaction force) and electromyographic (EMG) activity of leg and trunk muscles were tested in 27 subjects (age: 23 ± 3 years) during different time intervals (preactivation phase, braking phase, push-off phase). The performance of drop jumps under unstable compared to stable conditions produced a decrease in jump height (9 %, $p < 0.001$, $f = 0.92$) and an increase in peak ground reaction force (5 %, $p = 0.022$, $f = 0.72$), and time for braking phase (12 %, $p < 0.001$, $f = 1.25$). When performing drop jumps on unstable compared to stable surfaces, muscle activity was reduced in the lower extremities during the preactivation, braking and push-off phases (11-25 %, $p < 0.05$, $0.48 \leq f \leq 1.23$). Additionally, when landing on unstable compared to stable conditions, reduced lower limb muscle activities were observed during the preactivation phase (7-60 %, $p < 0.05$, $0.50 \leq f \leq 3.62$). Trunk muscle activity did not significantly differ between the test conditions for both, jumping and landing tasks. The present findings indicate that modified feedforward mechanisms in terms of lower leg muscle activities during the preactivation phase and/or possible alterations in leg muscle activity shortly after ground contact (i.e., braking phase) are responsible for performance decrements during jumping on unstable surfaces.

4.1.2 Introduction

In many sport disciplines, movements like vertical jumps or cutting maneuvers under stable and unstable conditions (e.g., opponent, sand, grass, turf) are essential components of athletic performance. In general, these activities are characterized by muscle actions in the stretch-shortening cycle (SSC). During the SSC, the preactivated muscle is lengthened in the eccentric (braking) phase followed by an immediate shortening in the concentric (push-off) phase (Komi and Gollhofer 1997). In SSC movements, performance during concentric actions is enhanced compared to isolated concentric actions (Komi and Gollhofer 1997, Komi 2000). In addition, jump-landing tasks with rapid changes in direction (e.g., cutting maneuvers) or with rapid deceleration phases (e.g., stopping and landing from a jump) are associated with an increased risk for non-contact injuries of the lower extremities (e.g., rupture of the anterior cruciate ligament) in sports (Hewett et al. 2005). Therefore, these movement patterns appear to be of major interest from an athletic as well as a health-related perspective.

Notably, performance during jumping and landing often occurs on relatively unstable surfaces (e.g., uneven natural turf in football, landings in gymnastics). It has been demonstrated that when performing lower limb exercises on unstable devices (e.g., Swiss balls, balance pads), force output is decreased (McBride et al. 2006, McBride et al. 2010, Zemková et al. 2012, Saeterbakken and Fimland 2013). In fact, Saeterbakken and Fimland (2013) reported significantly reduced force output during the performance of maximal isometric squats on the BOSU (i.e., both sides up) ball (19%) as well as on balance cones (24%) compared to stable surfaces (i.e., floor). Regarding the influence of surface conditions on power events such as SSC movements, it has been shown that performance measures were significantly affected by surface compliance (Bosco et al. 1997, Kerdok et al. 2002, Arampatzis et al. 2004). More specifically, in terms of maximal jumping, Arampatzis et al. (2004) observed an advantage of the compliant compared to the hard surface due to a higher ratio of positive to negative mechanical work accomplished by the subject during ground contact phase. However, it should be mentioned that this study investigated the effects of surface stability using stable/firm sprung surfaces of different stiffness levels. It is unresolved whether unstable/foam surfaces that are frequently used during athletic training and rehabilitation produce similar effects during jumping and landing as reported by Arampatzis (2004) for compliant surfaces.

Previously, it has been suggested that muscle actions on unstable as compared to stable surfaces increase electromyographic (EMG) activity in limb and trunk muscles (Anderson and Behm 2005). However, there is controversy in the literature regarding this issue, particularly for lower limb exercises (Anderson and Behm 2005, McBride et al. 2006, McBride et al. 2010, Bressel et al. 2009, Saeterbakken and Fimland 2013). For instance, McBride et al. (2010) showed a decrease in lower limb muscle activity on unstable as compared to stable surfaces. However, these studies reported the effects of surface instability during the performance of isometric and dynamic squats. To the authors' knowledge, there is no study available that investigated the influence of unstable surfaces on activity of lower limb as well as trunk muscles during maximal jumping and landing tasks. During jumping (i.e., drop jumps) and landing, it appears that EMG activity in lower limb muscles is preprogrammed during the preactivation phase (Dyhre-Poulsen et al. 1991, Avela et al. 1996) and affected by stretching loads (Avela et al. 1996, Komi and Gollhofer 1997, Fleischmann et al. 2010, Hoffrén et al. 2011) during the braking phase. In fact, it has been shown that muscle preactivation is related to the appearance and magnitude of spinal stretch reflexes during ground contact of drop jumps (Avela et al. 1996). In this regard, jumping and landing on unstable/foam surfaces may dampen the impact at ground contact which could reduce both, muscle preactivation and reflex activity.

Therefore, the objectives of this study were to investigate the effects of surface instability on (a) performance during drop jumps and landings and (b) activity of lower limb and trunk muscles. We hypothesized that performance measures together with EMG activity of lower limb and trunk muscles decrease during drop jumps and landings on unstable as compared to stable surfaces.

4.1.3 Methods

4.1.3.1 Participants

Fourteen healthy male and 13 healthy female subjects volunteered to participate in this study (Table 2). An a priori power analysis (Faul et al. 2007) with an assumed Type I error of 0.05 and a Type II error rate of 0.10 (90% statistical power) was calculated for measures of isometric squat performance (Saeterbakken and Fimland 2013) and revealed that 26 participants would be sufficient for finding a statistically significant main effect of test condition (i.e., stable vs. unstable surface). All participants can be classified as physically active according to the Freiburg questionnaire for everyday and sports-related activities (Frey et al. 1999) (Table 2). Further, our participants were experienced in plyometrics and their jump performance was screened before entering the study. None had any history of musculoskeletal, neurological, or orthopedic disorder that might have affected their ability to execute the experimental protocol. All participants gave their written informed consent before the start of the study. Local ethical permission was given, and all experiments were conducted according to the latest version of the declaration of Helsinki.

Table 2: Characteristics of participants by sex.

	Males (n = 14)	**Females (n = 13)**	**All (N = 27)**
Age [years]	22.9 ± 2.4	23.7 ± 3.2	23.3 ± 2.8
Body mass [kg] ***	74.4 ± 8.0	60.5 ± 9.0	67.7 ± 10.9
Body height [cm] **	179.9 ± 6.1	170.6 ± 8.9	175.4 ± 8.8
Body Mass Index [kg/m²] **	23.0 ± 2.0	20.7 ± 1.6	21.9 ± 2.1
Sports activity level [h/wk]	6.0 ± 2.6	6.3 ± 2.4	6.1 ± 2.4

Values represent means ± SD.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

4.1.3.2 Experimental procedure

A single-group, repeated-measures design was used to assess measures of performance and lower limb as well as trunk muscle activation during drop jump and landing tasks on stable and unstable surfaces. Following a standardized warm-up protocol for the lower limbs (3 times rope skipping for each with 30 s duration), the drop jumps and landings had to be performed on a one-dimensional force plate (Leonardo Mechanograph®; Novotec Medical GmbH, Pforzheim, Germany) under stable and unstable (i.e., AIREX® balance pad on top of the force plate) conditions in a randomized order. During the drop jumps, the dropping height amounted to 40 cm each for stable and unstable conditions. The participants stood on a platform with hands akimbo and had to initially step off the platform, drop down and land with both feet on the ground. In addition, they were instructed to jump off the ground as quickly and as high as possible. During the landing task, no instructions concerning the landing technique were given to avoid any coaching effect on natural performance. After a familiarization phase, one set including 3-5 repetitions was performed for each task (i.e., drop jump, landing) and condition (i.e., stable, unstable). A 1 minute rest was provided between sets.

4.1.3.3 Assessment of drop jump and landing performance

All drop jumps and landing trials on stable and unstable conditions were performed on a force plate which measures vertical ground reaction force (GRF) separately for the left and right leg. Synchronization of GRF and EMG data was achieved by analog-to-digital conversion on the same I/O board (TeleMyo 2400R G2 Analog Output Receiver, Noraxon®, Scottsdale, AZ, USA) with a sampling frequency of 1,500 Hz. For later analysis, the force signal was triggered on the instant of ground contact and averaged over 3 jumping and landing trials, respectively. Peak GRF was analyzed for jumping and landing tasks and normalized to body mass. Regarding drop jumps, GRF was used to determine contact time and jump height. More specifically, using a goniometer (Noraxon®, Scottsdale, AZ, USA) at the transverse axis of the knee joint of the dominant leg (Coren 1993), the contact time was divided into a braking and push-off phase. Jump height was calculated using the formula: jump height = $1/8 \times g \times t^2$, where g is the acceleration due to gravity and t is the flight time. In addition, given that ground contact time is a relevant parameter for drop jump performance, a performance index was calculated according to the following formula: performance index = jump height/contact time (Taube et al. 2012). In terms of the landing task on stable and unstable surfaces, the force plate and the goniometer were used to determine braking phases only.

4.1.3.4 Assessment of muscle activity during drop jumps and landings

Circular bipolar surface electrodes (Ambu®, type Blue Sensor P-00-S/50, Ag/AgCl, diameter: 13 mm, center-to-center distance: 25 mm, Ballerup, Denmark) were used to measure EMG activities of 4 leg muscles (m. vastus medialis [VM], m. biceps femoris [BF], m. gastrocnemius medialis [GM], m. tibialis anterior [TA]) and 2 trunk muscles (m. rectus abdominis, m. erector spinae lumbalis). The leg and trunk muscles were analyzed on the dominant side using the lateral preference inventory (Coren 1993). Electrodes were positioned on the muscle bellies according to the European recommendations for surface electromyography (Hermens et al. 1999). The longitudinal axes of the electrodes were in line with the direction of the underlying muscle fibers. Inter-electrode resistance was kept below 5 kΩ by shaving, slightly roughening, degreasing and disinfecting the skin. The EMG signals were amplified and recorded telemetrically (TeleMyo 2400T DTS, Noraxon®, Scottsdale, AZ, USA) to a computer at a sampling frequency of 1,500 Hz. After removal of heart muscle electrical activity artifacts from the trunk muscle signals by combining adaptive filter methods with a pattern recognition mode (Konrad 2005), the filtered (10-750 Hz bandwidth), full-wave rectified and integrated EMG (iEMG) signals of the investigated leg and trunk muscles were triggered on the instant of ground contact and averaged over 3 drop jump and landing trials respectively. To find out differences in muscle activity between test conditions, mean average voltage (MAV; defined as iEMG normalized relative to the integration time) was calculated for the preactivation phase (i.e., 100 ms prior to ground contact), the braking phase, and the push-off phase (drop jumps only) (Hoffrén et al. 2011). MAV values were normalized to the preactivation EMG value of the landing task on stable surface (Hoffrén et al. 2011). Additionally, in order to determine thigh and shank muscle activation during phases of expected reflex activity during the drop jumps, integrals were calculated for fixed 30 ms intervals. Thus, iEMG parameters of drop jumps were analyzed between 30-60 ms, 60-90 ms, 90-120 ms, and 120-150 ms and normalized to the 30-60 ms drop jump interval on stable surfaces (Fleischmann et al. 2010).

4.1.3.5 Statistical analyses

Data are presented as group mean values ± standard deviations (SD). After normal distribution was examined (i.e., Kolmogorov-Smirnov-Test), a 2 (sex: male, female) × 2 (surface: stable, unstable) analysis of variance (ANOVA) with surface as repeated within-subject factor was used to analyze muscle activation and performance parameters. Post-hoc tests with the Bonferroni-adjusted α were conducted to identify the comparisons that were statistically significant. The classification of effect sizes (f) was determined by calculating partial eta-squared (η_p^2). The effect size is a measure of the effectiveness of a treatment and it helps to determine whether a statistically significant difference is a difference of practical concern. Effect sizes can be classified as small ($0.00 \leq f \leq 0.24$), medium ($0.25 \leq f \leq 0.39$), and large ($f \geq 0.40$) (Cohen 1988). All analyses were performed using Statistical Package for Social Sciences (SPSS) version 21.0. The significance level was set at $p < 0.05$.

4.1.4 Results

4.1.4.1 Drop jump and landing performance

Results for measures of jumping and landing performance are presented in Table 3. The analyses of drop jumps and landings did not show any statistically significant sex × surface interactions. Only a tendency ($p = 0.071$, $f = 0.39$) of a sex × surface interaction was found for the braking phase during drop jumps. However, main effects for the factor surface were observed for jump performance measures (see Table 3). Under unstable as compared to stable drop jump conditions, jump height (9%, $p < 0.001$, $f = 0.92$) and performance index (12%, $p < 0.001$, $f = 0.83$) were significantly lower. This was accompanied by an increase in both, time for braking phase (12%, $p < 0.001$, $f = 1.25$) and peak GRF (5%, $p = 0.022$, $f = 0.72$). In terms of landing performance, no significant differences between test conditions were found for the parameter time for braking phase. A tendency towards an increase in peak GRF was noted under unstable as compared to stable conditions (10%, $p = 0.054$, $f = 0.40$).

Table 3: Variables of drop jump and landing performance by sex and surface condition.

	Men			**Women**			***p*-value**	
	Stable	Unstable	Δ, %	Stable	Unstable	Δ, %	Surface	Surface × Sex
Drop Jump								
Jump height [cm]	27.0 ± 4.0	24.7 ± 4.6	-9	24.4 ± 3.7	21.9 ± 3.7	-10	<0.001 [0.92]	0.896 [0.03]
Time for braking phase [ms]	108.5 ± 22.4	117.5 ± 21.4	8	105.3 ± 19.3	122.2 ± 15.6	16	<0.001 [1.25]	0.071 [0.39]
Time for push off phase [ms]	80.6 ± 20.5	79.8 ± 20.1	-1	82.6 ± 25.3	75.0 ± 18.9	-9	0.134 [0.32]	0.221 [0.26]
Performance index [m/s]	1.4 ± 0.3	1.3 ± 0.3	-9	1.3 ± 0.3	1.1 ± 0.3	-15	<0.001 [0.83]	0.443 [0.16]
Peak GRF [N/kg]	64.6 ± 13.0	70.0 ± 10.1	8	68.0 ± 11.2	69.6 ± 9.0	2	0.022 [0.72]	0.499 [0.14]
Landing								
Time for braking phase [ms]	237.8 ± 90.3	231.4 ± 116.0	-2	253.3 ± 166.5	230.4 ± 123.7	-9	0.491 [0.14]	0.696 [0.08]
Peak GRF [N/kg]	35.9 ± 5.9	41.6 ± 8.5	16	42.4 ± 10.9	44.2 ± 9.5	4	0.054 [0.40]	0.299 [0.21]

Values are means ± SD. Figures in brackets are effect sizes.
peak GRF = peak vertical ground reaction force

4.1.4.2 Muscle activity during drop jumps

No significant sex × surface interactions were found for measures of EMG activity during drop jumps. However, during the preactivation phase, muscle activity was significantly lower in TA (24%, $p < 0.001$, $f = 0.93$) and GM (21%, $p < 0.001$, $f = 1.23$) on unstable compared to stable surfaces (Fig. 1a). During the braking phase, only VM activity was significantly lower (15%, $p = 0.001$; $f = 0.73$) with instability (Fig. 1b). Additionally, surface-dependent activity reductions occurred in the VM (25%, $p = 0.005$; $f = 0.63$) and the GM (11%, $p = 0.03$; $f = 0.48$) during the push-off phase (Fig. 1c).

Regarding the fixed 30 ms time intervals, VM (19%, $p = 0.022$, $f = 0.50$) and BF (21%, $p = 0.017$; $f = 0.52$) muscle activities were significantly lower in the early 30-60 ms phase when jumping on unstable compared to stable surfaces (Fig. 2a and 2b). During later phases (i.e., 90-120 ms interval), only VM activity was statistically lower under unstable conditions (15%, $p = 0.018$; $f = 0.52$; Fig. 2a).

Jumping on unstable as compared to stable conditions did not produce any significant changes in trunk muscle activity (all $p > 0.05$).

4.1.4.3 Muscle activity during landings

No significant sex × surface interactions were found for measures of EMG activity during the landing task. However, lower limb muscle activity (i.e., VM, BF, TA, GM) were significantly lower during the preactivation phase (i.e., 7-60%) on unstable compared to stable surfaces (all $p < 0.05$, Fig. 1a). Effect sizes ranged from $f = 0.50$ to $f = 3.62$. During the braking phase, no statistically significant changes were observed between test conditions.

No statistically significant differences in trunk muscle activity were observed when landing on unstable as compared to stable conditions (all $p > 0.05$).

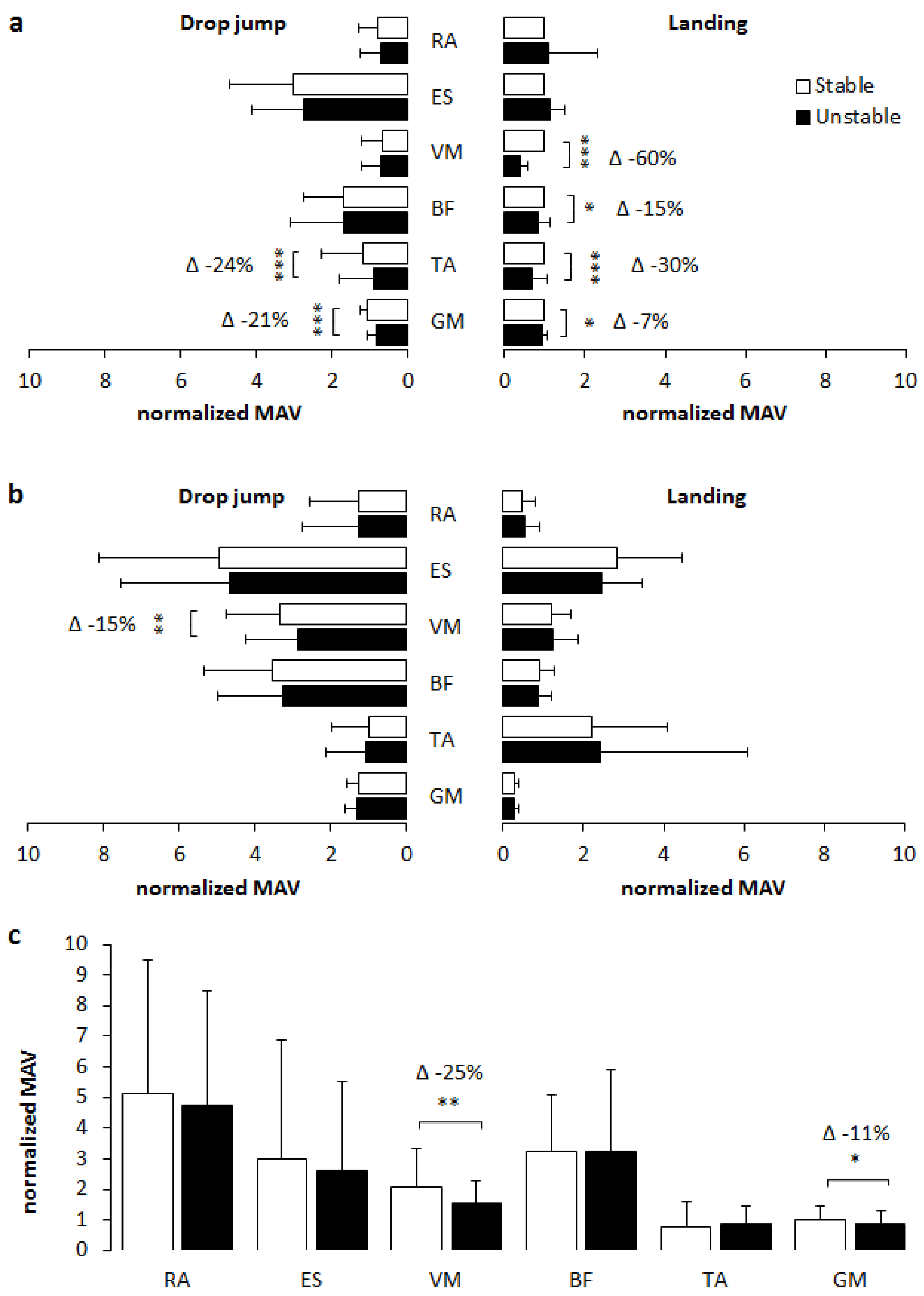

Figure 1: Muscle activity in drop jump and landing tasks during (a) preactivation, (b) braking and (c) drop jump push-off phase by surface condition. Mean average voltage (MAV) values are normalized on stable landing preactivation. RA = m. rectus abdominis, ES = m. erector spinae, VM = m. vastus medialis, BF = m. biceps femoris, TA = m. tibialis anterior, GM = m. gastrocnemius medialis.
*p < 0.05, **p < 0.01, ***p < 0.001

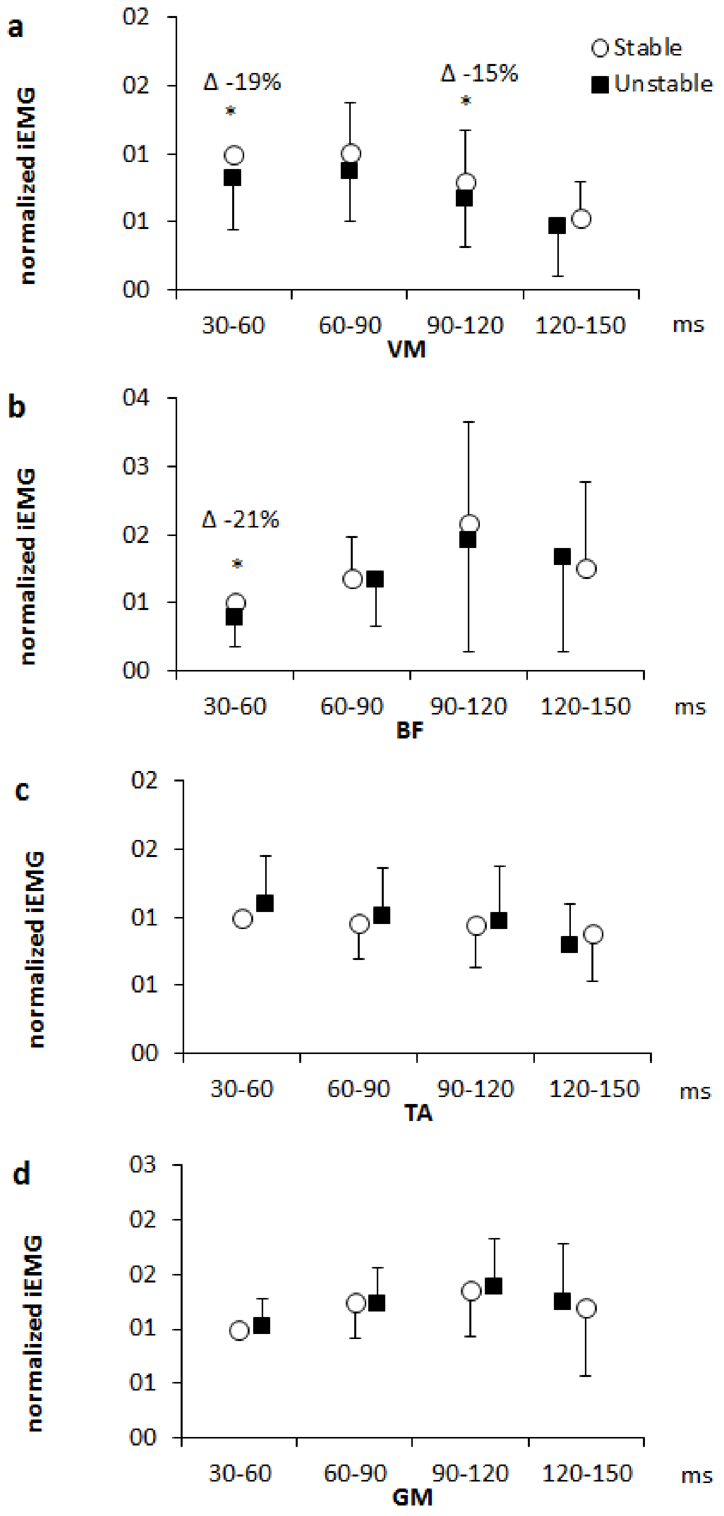

Figure 2: iEMG phases in drop jumps during the initial phase of contact by surface condition. iEMG values are normalized on the stable 30-60 ms interval. (a) VM = m. vastus medialis, (b) BF = m. biceps femoris, (c) TA = m. tibialis anterior, (d) GM = m. gastrocnemius medialis. Please note that for better visual inspection the vertical axes are not scaled the same way in all cases.

*$p < 0.05$

4.1.5 Discussion

To our knowledge, this is the first study that investigated the effects of surface instability on performance variables and on activity of lower extremity and trunk muscles during jumping and landing in healthy, young individuals. The main findings of this study can be summarized as follows: (a) drop jump performance (except for peak GRF) was significantly lower on unstable compared to stable surfaces, (b) landing performance was unaffected by surface instability, (c) neuromuscular activity of leg muscles was significantly lower during drop jumps (i.e., preactivation, braking and push-off phase) and landings (i.e., preactivation phase) on unstable compared to stable surfaces, and (d) trunk muscle activity during jumping and landing was not affected by surface condition.

4.1.5.1 Effects of surface instability on drop jump and landing performance

In many sport disciplines, unstable/foam surfaces are frequently used during athletic training and rehabilitation, to mimic sport-specific movements like vertical jumps or cutting maneuvers on unstable surfaces (i.e., sand, grass, turf). The present findings comply with a large body of literature regarding the effects of unstable/foam surfaces on force production (McBride et al. 2006, McBride et al. 2010, Zemková et al. 2012, Saeterbakken and Fimland 2013). In this regard, McBride et al. (2006) examined the effects of surface instability on force output during a multi-joint exercise of the lower limbs in young male athletes. The participants conducted squats on the floor (stable condition) and on inflatable balance disks (unstable condition). It was observed that maximal force and rate of force development were significantly lower on unstable compared to stable surfaces by 45 % and 40 %, respectively. More recently, Saeterbakken and Fimland (2013) reported that the performance of squats on BOSU balls and on balance cones, resulted in significantly lower force output on the BOSU ball (19 %) and the balance cone (24 %) compared to the stable floor condition in healthy men. However, it should be noted that these studies used isometric muscle actions, whereas we applied dynamic plyometric drills in the present study. A recently published study of Zemková et al. (2012) confirms our findings for the leg extensors in that they reported a reduction in peak and mean power output by 17 % and 16 %, respectively, during the performance of dynamic squats on a BOSU ball as compared to a stable condition. Further, Drinkwater et al. (2007) investigated performance measures (i.e., peak concentric/eccentric power, peak concentric force) during dynamic 10-repetition maximum squats on a wooden platform and on foam pads. The authors reported large effect sizes (i.e., $0.94 \leq f \leq 1.90$) for the factor surface condition in terms of reduced performance measures under unstable surface condition. In accordance with this finding, we also observed large effect sizes for the factor surface condition (i.e., jump height: $f = 0.92$; performance index: $f = 0.83$).

In terms of the effects of surface condition on jump performance, our findings of an instability related reduction in drop jump height (9 %) and performance index (12 %) are in contrast to the results of Arampatzis et al. (2004) who observed an increase in jump height (7 %) (calculated from the vertical take-off velocity of the subject's center of mass) on soft surfaces. This discrepancy in study findings can most likely be explained by differences in surface materials for the unstable condition. Whereas Arampatzis et al. (2004) applied firm sprung surfaces which have a beneficial effect on jump performance in terms of storage and return of elastic energy, we applied foam surfaces.

Interestingly, peak GRF was significantly higher when jumping on unstable as compared to stable surfaces. This may indicate that the mechanical properties (e.g., thickness, stiffness) of the unstable surface used in the present study (i.e., AIREX® balance pad) did not absorb impact loads properly. In fact, it has been shown that peak GRF values were similar when running (Ferris et al. 1998, Dixon et al. 2000) on surfaces of different stiffness levels. In the present study, even higher GRF values were found when jumping on unstable as compared to stable conditions. It can be speculated that mechanical and neuromuscular reasons may account for this finding. First, the applied balance pad did not absorb impact loads due to its material properties (i.e., foamed plastic). Second, after ground contact (i.e., braking and push-off phase), activity of leg muscles was lower when jumping on unstable as compared to stable surfaces. This may suggest that more force will be transferred to the knee joint and its passive restraints when muscle activity is lower. Together, these two factors may explain the observed higher GRF values.

4.1.5.2 Effects of surface instability on lower limb muscle activity during drop jumps and landings

In line with the findings regarding jump performance, EMG activity of the leg muscles was significantly lower during drop jumps on unstable compared to stable surfaces most likely resulting in the observed performance decrements during jumping. There is controversy in the literature regarding the effect of surface instability on lower limb muscle activity. In fact, McBride et al. (2006) reported a decrease in leg muscle activity when performing isometric squats on unstable surfaces. However, Saeterbakken and Fimland (2013) found a decrease in leg muscle activity in one muscle only (i.e., m. rectus femoris) during isometric squats on unstable surfaces whereas activity in all other analyzed leg muscles was unchanged. Further, McBride et al. (2010) were able to show a decrease in lower limb muscle activity during dynamic squats on unstable as compared to stable surfaces. Finally, Anderson and Behm (2005) even observed an increase in leg muscle EMG when performing dynamic squats on unstable elements. It appears that a specific methodological issue (absolute vs. relative loads) may account for the observed discrepancy in the literature regarding the effects of surface instability on muscle activity. In the study of Anderson and Behm (2005), the same absolute weight was applied for both test conditions (i.e., stable and unstable surfaces). Considering the lower maximal force output on unstable conditions (McBride et al. 2006, McBride et al. 2010, Saeterbakken and Fimland 2013), the absolute load (e.g., in percent of the one repetition maximum) assessed under stable conditions corresponds to a higher relative load under unstable conditions and may thus be responsible for the observed higher muscle activities under unstable conditions. In other words, higher muscle activities appear not to be caused by the level of surface stability/instability rather than by differences in relative load during the two test conditions. This is supported by findings from McBride et al. (2010) who reported reduced leg muscle activities during dynamic squats on unstable as compared to stable surfaces when the same relative load was used.

Our finding of reduced lower limb muscle activities during the preactivation phase of drop jumps (i.e., TA, GM) and landings (i.e., TA, GM, VM, BF) on unstable surfaces may indicate a modified feedforward activation pattern to prepare the neuromuscular system for the unstable condition. Given that the progressive decrease in stretching loads (e.g., by reducing dropping/falling height, body mass, or jumping distance) is related to lower preactivation levels of leg muscles (Dyhre-Poulsen et al. 1991, Avela et al. 1996, Komi and Gollhofer 1997, Fleischmann et al. 2010, Hoffrén et al. 2011), the observed lower muscle activities on unstable surfaces during the preactivation phase may result from an anticipated lower loading condition during jumping and landing.

Regarding muscle activity during ground contact, we observed lower EMG activity in the VM during the braking phase (15%) as well as in the VM and GM during the push-off phase (25% and 11%, respectively) when jumping on unstable as compared to stable surfaces. Moreover, shortly after ground contact (i.e., 30-60 ms), the VM (19%) and the BF (21%) revealed lower iEMG levels with instability. According to Fleischmann et al. (2010 EMG activity right before ground contact may influence muscle activation shortly after ground contact (i.e., 30-60-ms phase) which is associated with spinal stretch reflex induced activity. Functionally, this interaction is supposed to produce enhanced muscle stiffness and thus increased joint stability (Avela et al. 1996, Fleischmann et al. 2010). Interestingly, our finding of a lower preactivation level in the GM on unstable surfaces did not affect muscle activity in the early time interval (i.e., 30-60 ms) after ground contact during drop jumps. Consequently, the modified preactivation of TA and GM in response to different surfaces might not have a significant functional influence on muscle stiffness of those lower leg muscles during the initial phase of ground contact. Of note, VM and BF muscles showed similar preactivation levels during jumping on stable and unstable surfaces. However, their activation level was significantly lower in the 30-60-ms interval indicating that muscle stiffness may be altered in the thigh but not in the shank muscles to induce joint stability during drop jumps on different surfaces regardless of the preactivation level. Those findings are in accordance with results from Fleischmann et al. (2010) who observed load dependent modulations in iEMG activity (i.e., 30-60-ms interval) of the knee extensors but not the plantar flexors when performing lateral SSC jumps. Thus, external requirements other than preactivation intensity may be joint-specifically altered and may have influenced the specific responses of the thigh and shank muscles during the braking phase of drop jumps shortly after ground contact.

In terms of the landing task, the level of surface stability did not have an influence on muscle activity during ground contact. In contrast to the drop jumps, it appears that during landing lower limb muscle activity after the instant of ground contact is programmed and only marginally influenced by reflex activities (Dyhre-Poulsen et al. 1991). In fact, Dyhre-Poulsen et al. (1991) suggested that the suppression of reflex activities may change the muscle from a spring to a damping unit when suddenly stretched. Assuming that the unstable surface used in the present study did not absorb impact loads properly, it can be speculated that stretching loads caused by the fall did not change with instability during the landing tasks (as indicated by the unaltered peak GRF). Consequently, lower limb muscle activity after the instant of ground contact could be maintained in order to dampen similar stretching loads when landing on unstable surfaces.

4.1.5.3 Effects of surface instability on trunk muscle activity during drop jumps and landings

In terms of trunk muscle activity, no changes were observed for jumping and landing on stable versus unstable surfaces. These results are in contrast to the findings of Anderson and Behm (2005) and Bressel et al. (2009) who observed increased trunk muscle activity during the performance of dynamic lower body exercises on unstable devices (e.g., squats). However, in accordance with the reported studies investigating lower limb muscle activity with instability, it appears reasonable to argue that the studies of Anderson and Behm (2005) and Bressel et al. (2009) could be methodologically flawed by using the same absolute weight for the stable and unstable surface condition. This is in fact supported by findings from McBride et al. (2010) who reported similar activity for the spinal erector muscle during dynamic squats on stable and unstable surfaces when the same relative load was used.

4.1.6 Conclusion

In summary, the present study revealed decreases in drop jump performance (i.e., jump height and performance index) on unstable as compared to stable surface conditions. This appears to be caused by lower leg muscle activity during the preactivation and the braking phase on unstable compared to stable surfaces. The present findings indicate that modified feedforward mechanisms in terms of lower muscle activities during the preactivation phase and/or possible alterations in leg muscle activity shortly after ground contact (i.e., braking phase) are responsible for performance decrements during jumping on unstable surfaces. Given that trunk muscle activity was similar during jumping and landing on unstable and stable surfaces – even though performance was decreased – trunk muscles appear not to provide any additional contribution to trunk and lower-extremity stability under unstable compared to stable conditions. Based on these findings, it is suggested that plyometric exercises on stable rather than unstable surfaces should be incorporated in training if the goal is to enhance jump performance.

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4.2 Study 2

SEX-SPECIFIC EFFECTS OF SURFACE INSTABILITY ON DROP JUMP AND LANDING BIOMECHANICS

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4.2.1 Abstract

This study investigated sex-specific effects of surface instability on kinetics and lower extremity kinematics during drop jumping and landing. Ground reaction forces as well as knee valgus and flexion angles were tested in 14 males (age: 23 ± 2 years) and 14 females (age: 24 ± 3 years) when jumping and landing on stable and unstable surfaces. Jump height was found significantly lower (9 %, $p < 0.001$) when performing drop jumps on unstable compared to stable surface. Significantly higher peak ground reaction forces were observed when jumping on unstable as compared to stable surfaces (5 %, $p = 0.022$). Regarding frontal plane kinematics during jumping and landing, knee valgus angles were higher on unstable compared to stable surfaces (19-32 %, $p < 0.05$). Additionally, at onset of ground contact during landings, females showed higher knee valgus angles than males (222 %, $p = 0.027$). Sagittal plane kinematics indicated significantly smaller knee flexion angles (6-35 %, $p < 0.05$) when jumping and landing on unstable compared to stable surfaces. During drop jumps and landings, women showed smaller knee flexion angles at ground contact compared to men (27-33 %, $p < 0.05$). These findings imply that knee motion strategies were modified by surface instability and sex during drop jumps and landings.

4.2.2 Introduction

In several sport-related activities, performance often occurs on relatively unstable surfaces (e.g., jumping on uneven natural turf in soccer, landing in gymnastics). In this regard, it has been recommended that training must attempt to closely address the demands of the sport to adhere to the principle of training specificity (Behm and Anderson 2006). Thus, unstable devices such as Swiss balls and balance pads have become popular in athletic training and rehabilitation in order to mimic unstable sport surfaces.

It has frequently been demonstrated that surface conditions may affect biomechanical parameters of lower extremities during running (Derrick 2004, Kerdok et al. 2002), jumping (Arampatzis et al. 2004), and landing (McNitt-Gray et al. 1994). Notably, lower limb movements like jump-landing tasks followed by rapid changes in direction or by rapid deceleration phases are associated with an increased risk of sustaining non-contact injuries in lower extremities (e.g., rupture of the anterior cruciate ligament [ACL]) in sports (Arendt et al. 1999, Faunø and Wulff Jakobsen 2006). Earlier studies were able to elucidate different biomechanical factors like excessive knee abduction (valgus) (Herrington 2011, Myer et al. 2012) or insufficient knee flexion (Chappell et al. 2007, Derrick 2004, Myer et al. 2012) that are most likely responsible for an increased ACL injury risk during jump-landing tasks. Interestingly, during landing on different surfaces, McNitt-Gray et al. (1994) reported lower knee flexion angles on compliant as compared to hard gymnastic mats. In addition, Kerdok et al. (2002) reported lower maximum knee flexion angles with instability when running on surfaces with different stiffness levels. It has to be mentioned though that the last study investigated the effects of surface stability on submaximal plyometric exercises (i.e., running) using platforms with adjustable stiffness levels on a force-plate-fitted treadmill. As of now, it is unresolved whether unstable/foam surfaces that are frequently used during athletic training and rehabilitation produce similar effects during maximal plyometric exercises as those reported for landing on gymnastic mats (McNitt-Gray et al. 1994). Further, the two aforementioned studies (Kerdok et al. 2002, McNitt-Gray et al. 1994) investigated kinetics and sagittal plane kinematics during sport-specific movements only. Given that surface conditions during lower limb exercises have an impact on knee injury risk (Orchard 2002), kinematic factors in the frontal plane (e.g., knee valgus angles) should additionally be investigated because they could be affected by surface instability. To the authors' knowledge, there is no study available that scrutinized the effects of unstable surfaces on peak ground reaction force and on sagittal and frontal plane kinematic variables during jumping and landing tasks.

In addition, the prevalence of ACL injuries appears to be higher in females as compared to males (Arendt et al. 1999). In fact, sex differences have been shown for various kinematic variables that are associated with an increased injury risk during jump-landing tasks (Chappell et al. 2007, Gehring et al. 2009). For instance, Gehring et al. (2009) found higher knee valgus angles in females as compared to males when performing landings. Further, Chappell et al. (2007) reported lower knee flexion angles in females at onset of ground contact during vertical stop-jump tasks. Yet, there is no information available in the literature whether the sex factor has an effect on kinetic and kinematic parameters during jumping and landing on different surfaces (i.e., stable vs. unstable).

Therefore, the objectives of this study were to investigate sex-specific effects of surface instability during drop jumping and landing on lower extremity joint angles and ground reaction forces in healthy young adults. We hypothesized that frontal plane kinematics increase whereas sagittal plane kinematics decrease during drop jumps and landings on unstable as compared to stable surfaces, and that these tendencies are even more pronounced in females as compared to males.

4.2.3 Materials and methods

4.2.3.1 Participants

Fourteen healthy male (age: 23 ± 2 years, body height: 179.9 ± 6.1 cm, body mass: 74.4 ± 8.0 kg) and 14 healthy female subjects (age: 24 ± 3 years, body height: 170.5 ± 8.6 cm, body mass: 60.6 ± 8.7 kg) volunteered to participate in this study. An a priori power analysis (Faul et al. 2007) with an assumed Type I error of 0.05 and a Type II error rate of 0.10 (90 % statistical power) was calculated for measures of knee flexion kinematics (Dixon et al. 2000) and revealed that 27 participants would be sufficient for finding a statistically significant main effect of test condition (i.e., stable vs. unstable surface). All participants were classified as healthy and physically active (males: 6.0 ± 2.6 h/week, females: 6.3 ± 2.3 h/week) according to the Freiburg questionnaire for everyday and sports-related activities (Frey et al. 1999). None had any history of musculoskeletal, neurological, or orthopedic disorder that might have affected their ability to execute the experimental protocol. Further, our participants were experienced in plyometrics and their jump performance was screened regarding proper drop jumping technique as well as drop jump height and ground contact time before entering the study. All participants gave their written informed consent before the start of the study. The study was conducted according to the latest version of the declaration of Helsinki. It was approved by the local ethics committee, and it meets the ethical standards of the journal (Harriss and Atkinson 2013).

4.2.3.2 Experimental procedure

A repeated-measures design (stable vs. unstable surface) for two different groups (males vs. females) was used to assess kinetic and kinematic measures during drop jump and landing tasks. Following a standardized warm-up protocol (3 times rope skipping each for 30 s), drop jumps and landings had to be performed on a one-dimensional split force plate system (Leonardo Mechanograph®; Novotec Medical GmbH, Pforzheim, Germany) under stable and unstable (i.e., AIREX® balance pad on top of the force plate system) conditions as described previously (Prieske et al. 2013). In brief, participants stood on a platform with hands akimbo, stepped off the platform, dropped down from a height of 40 cm, and landed with both feet on the ground. The dropping height of 40 cm was selected to prevent that subjects' heels hit the force plate during ground contact and thus produce excessively high forces (Bobbert et al. 1987). Proper care was taken to assure a uniform dropping technique for all subjects (Kibele 1999). During the landing task, no instructions concerning the landing technique were given to avoid any coaching effect on natural performance. Further, when performing bouncing drop jumps, subjects were instructed to jump off the ground as quickly and as high as possible immediately after ground contact. After a familiarization phase, subjects conducted 1 set of 3-5 repetitions for each task (i.e., drop jumps, landings) and condition (i.e., stable, unstable) in a randomized order. A 1 minute rest was provided between sets.

4.2.3.3 Assessment of ground reaction force

All drop jump and landing trials on stable and unstable conditions were performed on a force plate system which measures vertical ground reaction force (GRF) separately for the left and right leg. Synchronization of GRF and knee flexion angle data was achieved by analog-to-digital conversion on the same I/O board (TeleMyo 2400R G2 Analog Output Receiver, Noraxon, Scottsdale, AZ, USA) with a sampling frequency of 1,500 Hz. For later analysis, the force signal was averaged over 3 drop jump and landing trials, respectively.

Regarding the drop jumping task, GRF signals were used to determine jump height. More specifically, jump height was calculated using the formula: jump height = $1/8 \times g \times t^2$, where g is the acceleration due to gravity and t is the flight time. Further, peak GRF and the impulse during the first 150 ms (IGRF150 ms) following ground contact were determined and normalized to body mass. The 150 ms time interval was chosen for the drop jump task because lower limb injuries have been shown to occur within this time interval during cutting movements (Gehring et al. 2013). Additionally, leg stiffness was calculated by dividing the corresponding GRF by the maximal vertical downward displacement of the center of mass (COM, approximated from the GRF signal using the spring mass model) and normalized to body mass (Arampatzis et al. 2004).

In terms of the landing task on stable and unstable surfaces, peak GRF was determined as well as the impulses during the first 50 ms (IGRF50 ms) and the subsequent 50 ms (IGRF50-100 ms) following ground contact (Gehring et al. 2009) and normalized to body mass. These time intervals were chosen because it has been shown that ACL loading and injuries occur immediately after ground contact when performing landing tasks (Pflum et al. 2004).

4.2.3.4 Assessment of lower extremity joint angles

During drop jump and landing, two-dimensional knee joint kinematics were assessed with a motion capture and analysis software (Simi Motion 7.3, Simi Reality Motion Systems GmbH, Unterschleissheim, Germany) using a high-speed camera (240 Hz; A602fc, Basler AG, Ahrensburg Germany). The camera was placed perpendicular to the frontal plane of the participants. Retroflective markers were located on the anterior superior iliac spine, patella, malleolus medialis, and the second metatarsal bone of the dominant side (Coren 1993). Thus, we were able to examine angular behavior of the knee in the frontal plane. Knee valgus motion was calculated for drop jumps and landings using the frame before ground contact and the frame with the knee being positioned in maximum medial (valgus) angle (Myer et al. 2012) (Figure 3). According to Myer et al. (2012), knee valgus motion was defined as the horizontal displacement between the knee coordinates of the two frames. Additionally, the knee valgus angle was determined (Herrington 2011) in the frame before ground contact (i.e., onset knee valgus angle) and the knee being in maximal downward displacement (i.e., down knee valgus angle; Figure 4). All frontal plane measures were analyzed using the mean of 3 drop jump and 3 landing trials. Reliability and validity of two-dimensional analysis of frontal plane knee kinematics have been reported elsewhere (McLean et al. 2005, Myer et al. 2012).

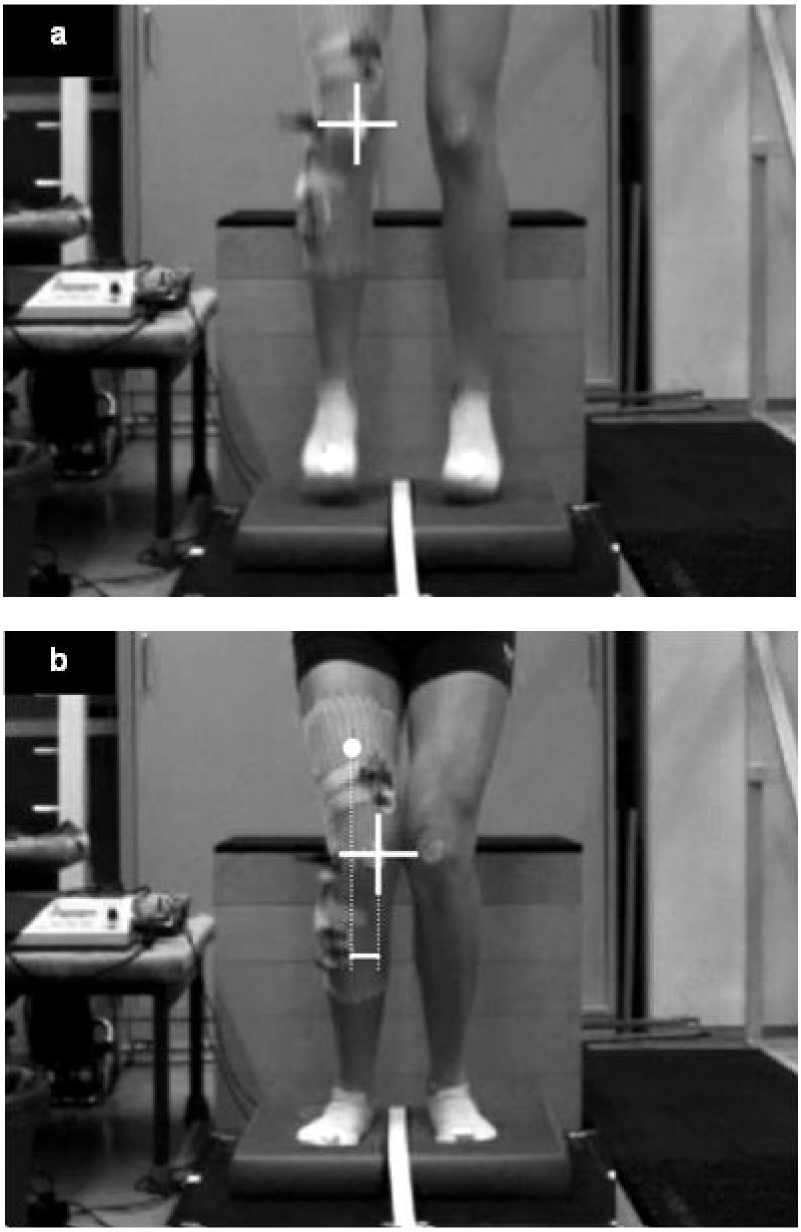

Figure 3: Knee valgus motion during drop jumping under unstable condition. The horizontal displacement between the two knee coordinates in the frontal plane at the frame prior to initial contact (a) and with maximum medial knee position (b) has been determined.

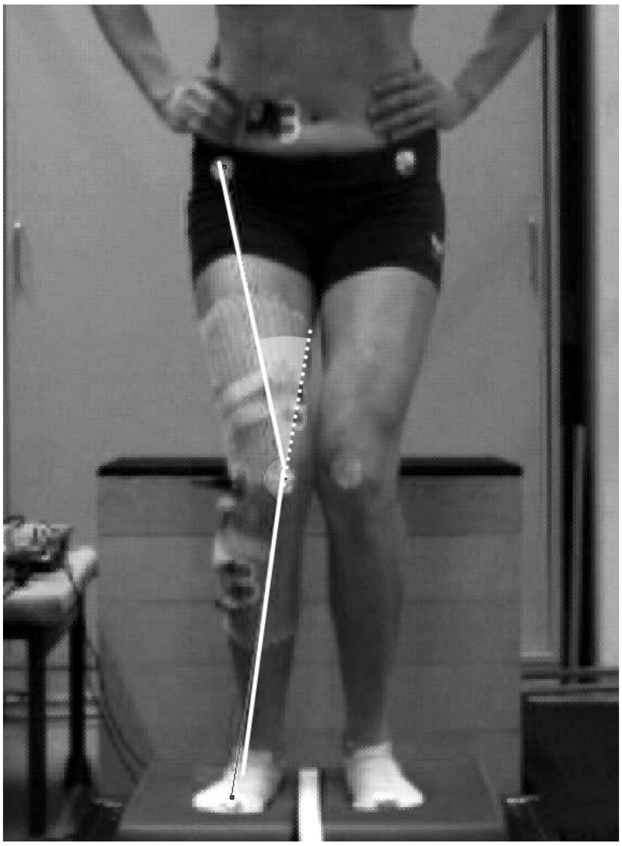

Figure 4: Down knee valgus angle during drop jumping under unstable condition.

The knee flexion angle of the dominant leg was assessed in sagittal plane by means of a goniometer (Noraxon®, Scottsdale, AZ, USA) that was attached to the transverse axis of the knee joint. The knee angle signals were amplified and recorded telemetrically (TeleMyo 2400T DTS, Noraxon, Scottsdale, AZ, USA) to a computer at a sampling frequency of 1,500 Hz. For later analysis, the knee flexion angle signal was triggered on the instant of ground contact and averaged over 3 drop jump and 3 landing trials, respectively. Knee joint flexion angles were determined at the onset of ground contact and when reaching maximum knee joint flexion during drop jumps and landings as well as at push-off during drop jumps. Additionally, the average angular velocities of knee joint flexion were calculated during the braking phase for drop jumps and during the first 50 ms (i.e., 0-50 ms) and the subsequent 50 ms (i.e., 50-100 ms) for landings in order to quantify sagittal knee joint motion in these time intervals (Gehring et al. 2009).

4.2.3.5 Statistical analyses

Descriptive data are presented as group mean values ± standard deviations (SD). After normal distribution was examined (i.e., Shapiro-Wilk-Test), a 2 (sex: male, female) × 2 (surface: stable, unstable) analysis of variance (ANOVA) with repeated measures on surface was used to analyze kinetic and kinematic parameters. Effect sizes (f) were determined by calculating partial eta-squared (η_p^2) in order to determine whether a statistically significant difference is a difference of practical concern. According to Cohen (1988), effect sizes can be classified as small ($0.00 \leq f \leq 0.24$), medium ($0.25 \leq f \leq 0.39$), and large ($f \geq 0.40$). All analyses were performed using Statistical Package for Social Sciences (SPSS) version 22.0. The significance level was set at $p < 0.05$.

4.2.4 Results

Overall, drop jump height was significantly reduced under unstable as compared to stable conditions (9 %, $p < 0.001$, $f = 0.92$). However, neither main effects of sex nor sex × surface interactions were detected.

4.2.4.1 Ground reaction force

Results for kinetic measures of drop jumps and landings are presented in Table 4. The analyses did not show any statistically significant main effects of sex and no sex × surface interactions (data not shown). However, significant main effects of surface were observed for drop jumps. Under unstable as compared to stable drop jump conditions, peak GRF (5 %, $p = 0.022$, $f = 0.48$) and GRF at maximal COM displacement (10 %, $p = 0.001$, $f = 0.73$) were significantly higher. This was accompanied by a significantly higher maximal COM displacement (9 %, $p < 0.001$, $f = 1.23$). In terms of landing performance, a tendency towards higher peak GRF (10 %, $p = 0.054$, $f = 0.40$) was noted under unstable as compared to stable conditions. In addition, the impulse during the second 50 ms following ground contact (i.e., IGRF50-100 ms) was significantly larger in the unstable condition (21 %, $p < 0.001$, $f = 1.43$).

Table 4: Kinetics during drop jumps and landings on stable and unstable surfaces. Force parameters are normalized to body mass. GRF = ground reaction force, IGRF = impulse, COM = center of mass.

	Males			**Females**			***p*-value (Effect Size)**	
	Stable	**Unstable**	**Δ [%)]**	**Stable**	**Unstable**	**Δ [%]**	**Surface**	**Sex**
Drop jump								
Peak GRF [N/kg]	64.6 ± 13.0	70.0 ± 10.1	8	68.0 ± 11.2	69.6 ± 9.0	8	0.022 (0.48)	0.692 (0.08)
IGRF 0-150 ms [Ns/kg]	6.1 ± 0.3	6.1 ± 0.4	1	6.0 ± 0.3	6.0 ± 0.3	1	0.228 (0.25)	0.245 (0.24)
Leg stiffness [kN/m/kg]	0.30 ± 0.07	0.30 ± 0.07	-2	0.30 ± 0.08	0.31 ± 0.07	2	0.918 (0.02)	0.740 (0.07)
GRF at maximal COM displacement [N/kg]	55.0 ± 6.6	59.3 ± 10.8	8	53.3 ± 8	59.7 ± 9.6	12	0.001 (0.73)	0.837 (0.04)
Maximal COM displacement [cm]	18.9 ± 2.4	20.5 ± 2.5	9	17.9 ± 1.9	19.6 ± 1.9	9	<0.001 (1.23)	0.279 (0.23)
Drop landing								
Peak GRF [N/kg]	35.9 ± 5.9	41.6 ± 8.5	16	42.4 ± 10.9	44.2 ± 9.5	4	0.054 (0.40)	0.118 (0.32)
IGRF 0-50 ms [Ns/kg]	1.0 ± 0.2	1.0 ± 0.3	0	1.0 ± 0.3	1.0 ± 0.3	5	0.570 (0.12)	0.878 (0.03)
IGRF 50-100 ms [Ns/kg]	1.5 ± 0.2	1.8 ± 0.4	23	1.6 ± 0.2	1.9 ± 0.3	20	<0.001 (1.43)	0.391 (0.18)

4.2.4.2 Lower extremity joint angles

Results for kinematic measures in the frontal plane of drop jumps and landings are presented in Table 5. Significant main effects of surface were observed for drop jump and landing tasks. When jumping on unstable surfaces, onset (22 %, $p = 0.039$, $f = 0.44$) and down knee valgus angle (19 %, $p = 0.041$, $f = 0.43$) were significantly larger as compared to the stable surface. In terms of landing, knee valgus angle at the onset of ground contact (32 %, $p = 0.012$, $f = 0.54$) was higher on unstable as compared to stable conditions. Additionally, significant main effects of sex were observed for landing tasks. That is, higher onset knee valgus angles ($p = 0.027$, $f = 0.47$) were found for women (stable: 3.6 ± 3.6 °, unstable: 4.4 ± 3.2 °) as compared to men (stable: 0.9 ± 2.6 °, unstable: 1.6 ± 2.8 °) during landing. Further, a tendency towards higher onset knee valgus angles ($p = 0.064$, $f = 0.39$) was detected for women (stable: 4.7 ± 3.6 °, unstable: 5.7 ± 4.1 °) as compared to men (stable: 2.4 ± 3.2 °, unstable: 2.9 ± 3.3 °) during drop jumps. However, no statistically significant sex × surface interactions were found for drop jumps and landings (data not shown).

Results for lower extremity joint angles in the sagittal plane are illustrated in Table 5. Significant main effects of surface were observed for drop jump and landing tasks. During drop jumps, maximum knee flexion (6 %, $p = 0.046$, $f = 0.43$) and knee flexion during push-off (35 %, $p < 0.001$, $f = 0.90$) were significantly lower under unstable as compared to stable surfaces. This was accompanied by a significantly lower knee flexion velocity during the braking phase (23 %, $p = 0.002$, $f = 0.72$) when jumping on unstable as compared to stable surfaces. In terms of landings, maximum knee flexion angle (7 %, $p = 0.005$, $f = 0.63$) and knee flexion velocity during the first 50 ms (38 %, $p < 0.001$, $f = 1.38$) were significantly lower on unstable than stable surfaces. However, during the subsequent 50-100 ms interval knee flexion velocity was higher (24 %, $p < 0.001$, $f = 0.98$). Further, significant main effects of sex were observed for drop jump and landing tasks. During drop jumps, significantly lower onset knee flexion angles ($p = 0.023$, $f = 0.50$) were found in women (stable: 14.2 ± 5.2 °, unstable: 13.7 ± 4.8 °) as compared to men (stable: 18.7 ± 5.7 °, unstable: 19.1 ± 6.5 °).In addition, significantly lower onset knee flexion angles ($p = 0.040$, $f = 0.44$) were observed in women (stable: 9.7 ± 6.7 °, unstable: 8.5 ± 5.9 °) as compared to men (stable: 14.0 ± 5.1 °, unstable: 13.6 ± 5.5 °) during landing tasks. Finally, the analyses of drop jumps and landings did not show any statistically significant sex × surface interactions (data not shown).

Table 5: Kinematics in the frontal and sagittal plane during drop jumps and landings on stable and unstable surfaces.

	Males			**Females**			***p*-value (Effect Size)**	
	Stable	**Unstable**	**Δ [%]**	**Stable**	**Unstable**	**Δ [%]**	**Surface**	**Sex**
Frontal plane								
Drop jump								
Knee valgus motion [cm]	2.1 ± 1.7	1.9 ± 1.6	-9	2.2 ± 1.3	2.0 ± 1.2	-7	0.320 (0.20)	0.796 (0.05)
Onset knee valgus angle [°]	2.4 ± 3.2	2.9 ± 3.3	23	4.7 ± 3.6	5.7 ± 4.1	21	0.039 (0.44)	0.064 (0.39)
Down knee valgus angle [°]	3.6 ± 3.7	5.0 ± 3.4	38	5.3 ± 3.2	5.6 ± 3.0	7	0.041 (0.43)	0.365 (0.18)
Drop landing								
Knee valgus motion [cm]	1.7 ± 1.7	1.4 ± 1.6	-18	1.8 ± 1.2	1.6 ± 1.1	-7	0.250 (0.24)	0.711 (0.07)
Onset knee valgus angle [°]	0.9 ± 2.6	1.6 ± 2.8	78	3.6 ± 3.6	4.4 ± 3.2	22	0.012 (0.54)	0.027 (0.47)
Down knee valgus angle [°]	-2.2 ± 10.2	-1.6 ± 6.3	28	3.1 ± 5.6	2.8 ± 6.7	-10	0.869 (0.03)	0.077 (0.37)
Sagittal plane								
Drop jump								
Onset knee flexion angle [°]	18.7 ± 5.7	19.1 ± 6.5	2	14.2 ± 5.2	13.7 ± 4.8	-4	0.963 (0.01)	0.023 (0.50)
Maximum knee flexion angle [°]	36.7 ± 9.8	35.3 ± 10.4	-4	33.9 ± 9.6	31.0 ± 7.2	-8	0.046 (0.43)	0.328 (0.20)
Push-off knee flexion angle [°]	8.8 ± 5.3	4.8 ± 5.6	-46	7.5 ± 7.6	5.9 ± 8.2	-21	<0.001 (0.90)	0.971 (0.01)
Knee flexion velocity [°/s]	172.7 ± 92	138.7 ± 71.8	-20	195.1 ± 72.7	144.7 ± 48.6	-26	0.002 (0.72)	0.597 (0.11)

Drop landing								
Onset knee flexion angle [°]	14.0 ± 5.1	13.6 ± 5.5	-3	9.7 ± 6.7	8.5 ± 5.9	-13	0.272 (0.23)	0.040 (0.44)
Maximum knee flexion angle [°]	57.2 ± 12.7	53.2 ± 15.3	-7	54.3 ± 16.5	50.0 ± 14.2	-8	0.005 (0.63)	0.590 (0.11)
Knee flexion velocity 0-50 ms [°/s]	315.2 ± 156.1	195.4 ± 99.7	-38	319.2 ± 154.8	196.9 ± 104.5	-38	<0.001 (1.38)	0.956 (0.01)
Knee flexion velocity 50-100 ms [°/s]	281.3 ± 112.8	352.2 ± 144.4	25	282.9 ± 133.7	346.2 ± 151.6	22	<0.001 (0.98)	0.966 (0.01)

4.2.5 Discussion

The present study investigated the effects of surface instability on kinetic and particularly on lower extremity kinematic variables in frontal and sagittal plane during drop jumps and landings in healthy, young males and females. The main findings of this study can be summarized as follows: (a) peak GRF and IGRF50-100 ms were larger during drop jumps and landings on unstable as compared to stable surfaces, (b) knee valgus was higher under unstable as compared to stable conditions during drop jumps and landings, (c) knee flexion was lower during drop jumps and landings on unstable as compared to stable conditions, and (d) females revealed different knee joint kinematics during ground contact of drop jump and landing tasks (i.e., lower knee valgus, higher knee flexion) as compared males.

4.2.5.1 Effects of surface instability on ground reaction force

In many sport disciplines, unstable/foam surfaces have become popular in athletic training and rehabilitation to mimic unstable surfaces (i.e., sand, grass, turf) during sport-specific movements such as vertical jumps or cutting maneuvers. Regarding the effects of unstable/foam surfaces on peak GRF during drop jumps, the present findings comply with studies investigating the effect of surface condition while running (Kerdok et al. 2002) and while performing jump-landing tasks (McNitt-Gray et al. 1994). For instance, Kerdok et al. (2002) examined healthy, male subjects running over 5 different levels of surface stiffness on a force-plate-fitted treadmill. It was found that peak GRF was significantly higher on the most compliant as compared to the stiffest surface. Further, in the study of McNitt-Gray et al. (1994) male and female collegiate gymnasts performed competition-style jump-landing tasks on 3 different surfaces (i.e., no mat, stiff mat, soft mat). The authors reported higher peak GRF in the mat conditions compared to the no mat condition. McNitt-Gray et al. (1994) suggested that smaller knee flexion angles on compliant surfaces may alter the vertical impulse characteristics. In fact, it has been stated that larger knee angles during ground contact (i.e., more extended legs) can increase the forces experienced by the body when running (Derrick 2004). Thus, given that in the present study maximum knee flexion angles were smaller with instability, it can be argued that changes in sagittal plane kinematics accounted for higher peak GRF and impulse values during drop jumps and landings on the unstable surface.

In terms of GRF values during jumping tasks, the relationship between vertical force and vertical COM displacement from touch down to the lowest COM position has been defined as leg stiffness (Arampatzis et al. 2004). In this regard, it has been shown that jumping on compliant surfaces provides an increase in leg stiffness in order to maintain overall stiffness of the subject-surface system (Ferris and Farley 1997). In the present study, no changes in leg stiffness were observed with instability. This is partly in line with results from Arampatzis et al. (2004) who did not find any significant changes in leg stiffness when analyzing drop jumps on surfaces of different stiffness levels. However, the authors reported similar vertical force and COM displacement values for the different surface conditions. In contrast, we found that GRF as well as maximal vertical COM displacement were larger with instability, thus counteracting leg stiffness changes. Partial discrepancy in our study findings and results reported in the literature can most likely be explained by differences in surface materials to induce unstable conditions and/or in different jumping task. Whereas we applied foam surfaces which is highly demanding in terms of postural control during ground contact, Arampatzis et al. (2004) and Ferris and Farley (1997) applied firm sprung surfaces. Further, in contrast to maximal drop jumping in the present study, Ferris and Farley (1997) investigated submaximal jumping performance (i.e., hopping).

4.2.5.2 Effects of surface instability and sex on lower extremity joint angles

Several kinematic measures such as excessive knee valgus (Herrington 2011, Myer et al. 2012) or insufficient knee flexion (Chappell et al. 2007, Derrick 2004, Myer et al. 2012) have been determined as risk factors that appear to contribute to non-contact ACL injuries during jump-landing tasks. Further, it has also been argued that surface conditions during the performance of lower limb exercises (i.e., jumping, landing) may affect knee injury risk (Orchard 2002). The findings of the present study showed that surface instability produced small but significantly higher knee valgus angles during drop jumps and landings as compared to stable surfaces. Given that higher knee valgus angles are associated with an increased ACL injury risk (Herrington 2011, Myer et al. 2012), it can be argued that jumping and landing on stable/firm surfaces is safer compared to unstable/foam surfaces. In terms of the underlying mechanism, it can be speculated that changes in neuromuscular control of the knee could be responsible for higher knee valgus angles. In fact, a balanced medial-to-lateral muscle control of the knee joint is necessary to avoid excessive frontal plane motion in the knee (Gehring et al. 2009). Recently, Prieske et al. (2013) found lower activation particularly in the vastus medialis muscle during drop jumps and landings on unstable compared to stable surfaces. Thus, the applied balance pad in the present study appears to challenge the neuromuscular system to properly maintain control of the knee during drop jumps and landings.

In terms of sex effects in frontal plane kinematics during jumping, Chappell et al. (2007) failed to show significant main effects of sex regarding onset knee valgus angles during vertical stop-jump tasks. In accordance with this finding, the present study revealed only a tendency towards higher onset knee valgus angles in females compared to males during drop jumps. This could be due to the fact that females reached similar jump heights as compared to males. Thus, the existent expertise of our female subjects in drop jump performance could have affected their frontal plane knee motion behavior in a sense that excessive knee valgus was prevented. However, when performing landing tasks, females showed higher knee valgus angles at the instant of ground contact (i.e., onset knee valgus angle) compared to males. This finding is consistent with the literature regarding the effects of sex on frontal plane kinematics during landings (Gehring et al. 2009). Gehring et al. (2009) investigated the effects of lower limb fatigue on measures of lower extremity kinematics during landings with a special focus on sex-specific behavior. The authors reported significant main effects of sex for onset and maximum knee valgus angles. This may indicate an increased injury risk in females when landing. Thus, it can be concluded that males and females exhibit similar knee valgus profiles during drop jumps on stable and unstable surfaces. However, during landings, females show higher valgus angles.

Concerning sagittal plane kinematics, the present findings revealed that participants performed jumping and landing tasks with larger knee angles during ground contact (i.e., more extended legs) on unstable compared to stable surfaces. Consequently, a lower knee flexion velocity was found with instability during the braking phase of the drop jumps and during the first 50 ms time interval when landing. This finding is supported by studies that investigated the effects of surface condition on kinematic parameters during running (Kerdok et al. 2002) and landing (McNitt-Gray et al. 1994). More specifically, Kerdok et al. (2002) reported lower maximum knee flexion angles when running on the most compliant as compared to the stiffest surface. In addition, McNitt-Gray et al. (1994) found significantly lower maximum knee flexion angles as the compliance of gymnastic mats increased during landing tasks. It was suggested that knee flexion adjustments take place to maintain the combined stiffness of the body-surface-system (McNitt-Gray et al. 1994) and to even increase leg stiffness on more compliant surfaces (Kerdok et al. 2002). Interestingly, despite lower knee flexion angles with instability, there was no surface effect on leg stiffness during drop jumps because both, maximal vertical COM displacement and GRF adapted concurrently. Given that ankle and hip kinematics also contribute to the vertical COM displacement, it can be speculated that maximal vertical COM displacement during drop jumps on the balance pad was larger due to greater dorsal extensions of the ankle joint and/or larger hip flexions.

In terms of main effects of sex on knee flexion, the analysis revealed larger knee angles during ground contact (i.e., more extended leg) of jumping and landing tasks in females compared to males. Similar findings have been described by Chappell et al. (2007) who recently observed lower knee flexion angles in females compared to males at the instant of ground contact during vertical stop-jump tasks. The authors interpreted the lower knee flexion angle as a potential knee injury risk factor that produces increased ACL loadings. Thus, based on the findings of Chappel et al. (2007) and the results of the present study, it can be hypothesized that – in spite of their high performance level – females are at greater risk of sustaining a non-contact ACL injury when jumping and landing on unstable surfaces.

4.2.6 Conclusion

In summary, the present study revealed modified knee motion strategies in terms of larger knee valgus angles and smaller knee flexion angles on unstable as compared to stable surface conditions. This may have resulted in larger peak GRF values (during drop jumps) and impulse values (during landings) with instability. It was also shown that sagittal plane kinematics specifically changed in order to maintain leg stiffness on the unstable surface during drop jumps. However, unstable surfaces appear to be more challenging to maintain neuromuscular control and biomechanical integrity (i.e., in frontal and sagittal plane motion) of the knee during drop jumps and landings. Compared to men, women showed modified knee motion strategies during jump-landing tasks. This may indicate why ACL injury risk is particularly high in females. Based on these findings, it is suggested that neuromuscular training programs should be conducted with the goal to improve neuromuscular control of the knee joint (e.g., balance training, instability resistance training) before incorporating unstable surfaces in plyometric training programs particularly in females.

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4.3 Study 3

ROLE OF THE TRUNK DURING DROP JUMPS ON STABLE AND UNSTABLE SURFACES

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4.3.1 Abstract

The present study investigated associations between trunk muscle strength, jump performance, and lower limb kinematics during drop jumps on stable and unstable surfaces. Next to this behavioral approach, correlations were also computed on a neuromuscular level between trunk and leg muscle activity during the same test conditions. Twenty-nine healthy and physically active subjects (age: 23 ± 3 years) were enrolled in this study. Peak isokinetic torque (PIT) of the trunk flexors and extensors was assessed separately on an isokinetic device. In addition, tests included drop jumps (DJ) on a force plate under stable and unstable (i.e., balance pad on top of the force plate) surfaces. Lower limb kinematics as well as electromyographic activity of selected trunk and leg muscles were analyzed. Significant positive but small correlations ($.50 \leq r \leq .66$, $p < 0.05$) were detected between trunk extensor PIT and athletic performance measures (i.e., DJ height, DJ performance index), irrespective of surface condition. Further, significant negative but small correlation coefficients were examined between trunk extensor PIT and knee valgus motion under stable and unstable surface conditions ($-.48 \leq r \leq -.45$, $p < 0.05$). Additionally, significant positive but small correlations ($.45 \leq r \leq .68$, $p < 0.05$) were found between trunk and leg muscle activity, irrespective of surface condition. Behavioral and neuromuscular data from this study indicate that, irrespective of the surface condition (i.e., jumping on stable or unstable ground), the trunk plays a minor role for leg muscle performance/activity during DJ. This implies only limited effects of trunk muscle strengthening on jump performance in the stretch shortening cycle.

4.3.2 Introduction

In many sport disciplines, plyometric muscle actions like vertical jumps or cutting maneuvers are essential components of athletic performance. The execution of plyometric movements enables performance enhancements during the concentric phase as compared to isolated concentric actions (Komi and Gollhofer 1997). Notably, performance during jumping often occurs on relatively unstable surfaces (e.g., uneven natural turf in football, landings in gymnastics) potentially affecting neuromuscular (Prieske et al. 2013) and kinematic (Arampatzis et al. 2004, Prieske et al. 2014) variables. Indeed, significant performance decrements (i.e., force, jump height) as well as changes in muscle activity were reported during lower limb exercises (i.e., squats, drop jumps) on unstable compared to stable surfaces (Saeterbakken and Fimland 2013, Prieske et al. 2013). Notably, when performing exercises with the same absolute load, activity of trunk muscles increases with instability (Anderson and Behm 2005, Bressel et al. 2009). Thus, it can be argued that the trunk is particularly important for lower limb muscle performance on unstable surfaces.

Generally, trunk muscles seem to have a stabilizing function during jump-landing tasks. In support of this notion, the importance of trunk muscle strength has recently been promoted for enhancing athletic performance (Nesser et al. 2008, Kibler et al. 2006, Sharma et al. 2012) and/or maintaining musculoskeletal health (Jamison et al. 2013, Willson et al. 2005). For instance, Nesser et al. (2008) reported significant relationships ($.40 \leq r \leq .59$) between various isometric trunk muscle endurance tests (i.e., trunk extension/flexion; left/right bridge) and countermovement jumps on stable surface in male football players. However, Nesser et al. (2008) applied trunk muscle endurance tests comprising submaximal isometric muscle actions that do not adequately illustrate the importance of maximal (dynamic) trunk muscle strength/torque for athletic performance. According to Henneman’s size principle (Henneman 1957), an orderly recruitment of progressively larger single motor units in movements of increasing intensity (e.g., force level) was observed in humans (Milner-Brown et al. 1973, Desmedt and Godaux 1977). Consequently, it can be argued that due to lower force levels in submaximal trunk muscle endurance tests, the proportion of activated fast-twitch fibers is lower compared to the activation level during athletic movements at maximal muscle actions. Thus, testing dynamic maximal trunk muscle strength instead of isometric trunk muscle endurance may be more appropriate to evaluate the role of trunk muscles for athletic performance (e.g., jumping). Further, in the study of Nesser et al. (2008), behavioral variables were analyzed only. Next to this behavioral approach, assessing neuromuscular data could add complementary and in-depth information on the role of the trunk during jump tasks. In fact, previous studies indicate an association between neuromuscular parameters of trunk and leg muscles (Hodges and Richardson 1997, Myer et al. 2008). Specifically, Kibler et al. (2006) argued that higher levels of proximal muscle activity prior to and during actual motor performance can also increase levels of muscle activation in the extremities, improving their neuromuscular capability to support or propel the extremities. Thus, it seems reasonable to argue that there is an association between trunk and leg muscle activation during jumping tasks. However, the relationship between trunk and leg muscle activity during jumping is still unresolved.

In addition, there appears to be a connection between different variables of trunk muscle performance/activity and lower limb kinematics during jump-landing tasks (Jamison et al. 2013, Zazulak et al. 2007). For instance, Zazulak et al. (2007) reported that decreased neuromuscular trunk control may contribute to increased valgus motion of the lower extremity. Further, Jamison et al. (2013) observed significant associations between level of trunk muscle activation and knee abduction moments (r = .49) during run-to-cut maneuvers on stable surface in young healthy subjects. More specifically, the authors argued that higher neuromuscular activation of the trunk extensor muscles results in increased knee abduction moments through stiffening of the spine. This produces limited sagittal plane trunk flexion as well as upper body kinetic energy absorption (Jamison et al. 2013). Thus, it seems reasonable to argue that trunk muscle strength is also associated with frontal plane kinematics (i.e., knee valgus motion).

To the authors' knowledge, there is no study available that scrutinized potential associations between trunk muscle strength and knee valgus motion during jump tasks. In addition, there is still a gap in our knowledge concerning the role of the trunk during jumping on stable and unstable surfaces. Therefore, the objectives of this study were to investigate associations between trunk muscle strength, jump performance, and lower limb kinematics (e.g., knee valgus motion) during drop jumps on stable and unstable surfaces. Next to this behavioral approach, correlations were also computed on a neuromuscular level between trunk and leg muscle activity during the same test conditions. Based on the relevant literature (Hodges and Richardson 1997, Anderson and Behm 2005, Myer et al. 2008, Nesser et al. 2008, Bressel et al. 2009, Sharma et al. 2012, Jamison et al. 2013, Prieske et al. 2013, Saeterbakken and Fimland 2013, Zazulak et al. 2007, Prieske et al. 2014), we expect significant correlations between trunk muscle strength, drop jump performance, and lower limb kinematics as well as between trunk and leg muscle activity during drop jumps which are more pronounced under unstable compared to stable surface conditions.

4.3.3 Material and methods

4.3.3.1 Participants

With reference to the study of Nesser et al. (2008), an a priori power analysis (Faul et al. 2007) with an assumed type 1 error of 0.05 and a statistical power of 80% (type 2 error rate of 0.20) was conducted. The analysis revealed that 29 subjects would be sufficient to find statistically significant correlations between measures of trunk and drop jump performance. Finally, after screening for drop jump performance (i.e., proper drop jump technique with a ground contact time ≤ 230 ms), 14 healthy male and 15 healthy female subjects were enrolled in this study. All participants were experienced in plyometrics and can be classified as physically active according to the Freiburg questionnaire for everyday and sports activities (Frey et al. 1999). Participants’ baseline characteristics are presented in Table 6. None had any history of musculoskeletal, neurological, or orthopedic disorder that might have affected their ability to execute the experimental protocol. Written informed consent has been received from all of the participants before the start of the study. Local ethical permission was given (Ethical commission of the University of Potsdam, Submission No. 28/2013), and all experiments were conducted according to the latest version of the declaration of Helsinki.

Table 6: Characteristics of participants by sex.

Characteristics	**Men (n = 14)**	**Women (n = 15)**	**All (N = 29)**
Age [years]	22.9 ± 2.4	23.8 ± 3.3	23.3 ± 2.9
Body mass [kg] ***	74.4 ± 8.0	60.3 ± 8.4	67.1 ± 10.8
Body height [cm] **	179.9 ± 6.1	169.6 ± 8.9	174.6 ± 9.2
Body Mass Index [kg/m²] **	23.0 ± 2.0	20.9 ± 1.6	21.9 ± 2.0
Sports activity level [h/wk]	6.0 ± 2.6	6.6 ± 2.6	6.3 ± 2.6
Trunk muscle strength			
Flexors PIT [Nm/kg] ***	2.8 ± 0.2	2.1 ± 0.2	2.4 ± 0.4
Extensors PIT [Nm/kg]	3.6 ± 0.5	3.4 ± 0.7	3.5 ± 0.6
Performance measures (stable condition)			
Drop jump height [cm]	27.0 ± 4.0	24.7 ± 3.7	25.9 ± 3.9
Drop jump performance index [m/s]	1.4 ± 0.3	1.3 ± 0.3	1.4 ± 0.3
Knee valgus motion [cm]	2.1 ± 1.7	2.2 ± 1.3	2.1 ± 1.5
Performance measures (unstable condition)			
Drop jump height [cm]	24.7 ± 4.6	21.9 ± 3.7	23.4 ± 4.4
Drop jump performance index [m/s]	1.3 ± 0.3	1.1 ± 0.3	1.2 ± 0.3
Knee valgus motion [cm]	1.9 ± 1.6	2.0 ± 1.2	2.0 ± 1.4

Values represent means ± SD. PIT = peak isokinetic torque
**$p < 0.01$, ***$p < 0.001$

4.3.3.2 Procedure

A single-group, repeated-measures design was used to assess behavioral (i.e., maximal trunk muscle strength, jump height, performance index, knee valgus motion) and neuromuscular (i.e., trunk and leg muscle activity) variables during drop jumps on stable and unstable surfaces. In order to minimize intra-subject variability, knee valgus motion and muscle activity were determined on the dominant side. Leg dominance was assessed using the lateral preference inventory by Coren (1993). Subjects started with a standardized warm-up program for the trunk muscles (i.e., 1 min of submaximal concentric trunk flexions/extensions at a velocity of 60 °/s) that was followed by the assessment of maximal trunk muscle strength on an isokinetic device (Con-Trex TP1000; Physiomed Elektromedizin AG, Schnaittach/Laipersdorf, Germany). Thereafter, participants conducted a warm-up protocol for the lower extremities (i.e., 3 × rope skipping for 30 s each). Thereafter, drop jumps had to be performed on a force plate (Leonardo Mechanograph®; Novotec Medical GmbH, Pforzheim, Germany) under stable and unstable (i.e., AIREX® balance pad on top of the force plate) conditions. The participants stood on a platform with hands akimbo. One foot was moved in anterior direction before subjects stepped off the platform with the other foot. They dropped down from a height of 40 cm and jumped off the ground as quickly and as high as possible immediately after ground contact. Subjects were allowed to select the preferred foot for stepping off the platform. Proper care was taken to assure a uniform dropping technique for all subjects (Kibele 1999). After a familiarization phase, participants conducted in a randomized order 1 set of 3-5 repetitions for each condition (i.e., stable, unstable). A 1 minute rest was provided between sets.

4.3.3.3 Assessment of trunk muscle strength

Peak isokinetic torque (PIT) of the trunk extensors and flexors was measured using an isokinetic dynamometer. The maximum error of the torque sensor was < 1% full scale (1,000 Nm) and acceptable test-retest reliability (intraclass correlation coefficients ranged between .74 and .91) has been reported previously (Baur et al. 2010). PIT was defined as the maximal voluntary torque value determined under isokinetic conditions. After subject-specific adjustment of the dynamometer, the participants were firmly fixed in a standing position using straps around the knee, the hip, and the upper torso. The trunk movement was allowed from 45° flexion to 10° extension (i.e., range of motion of 55°; 0° corresponds to a standing upright position). A standardized warm-up was conducted performing submaximal concentric actions at a velocity of 60 °/s. Thereafter, participants performed maximal isokinetic testing. Subjects were thoroughly encouraged to act “as forcefully as possible” during each trial. Maximal isokinetic trunk flexion and extension actions were investigated performing a five-trial sequence of trunk flexion-extension in concentric mode at a velocity of 60 °/s (Baur et al. 2010). The mean of the 5 test trials for PIT was calculated and normalized to body mass.

4.3.3.4 Assessment of drop jump performance and lower limb kinematics

Drop jump height and ground contact time under stable and unstable conditions were determined using the ground reaction force (GRF) signals of the force plate which measures GRF separately for the left and right leg. Synchronization of GRF and electromyographic

(EMG) data was achieved by analog-to-digital conversion on the same I/O board (TeleMyo 2400R G2 Analog Output Receiver, Noraxon, Scottsdale, AZ, USA) with a sampling frequency of 1,500 Hz (Figure 5). Drop jump height was calculated using the formula: drop jump height = 1/8 × g × t^2, where g is the acceleration due to gravity and t is the flight time. In addition, considering the time of ground contact as a relevant parameter for drop jump performance, the ratio between drop jump height and contact time was calculated and expressed as the drop jump performance index (drop jump performance index = drop jump height/contact time) (Prieske et al. 2013). For later analyses, the mean of 3 drop jump trials was calculated for the parameters drop jump height and drop jump performance index.

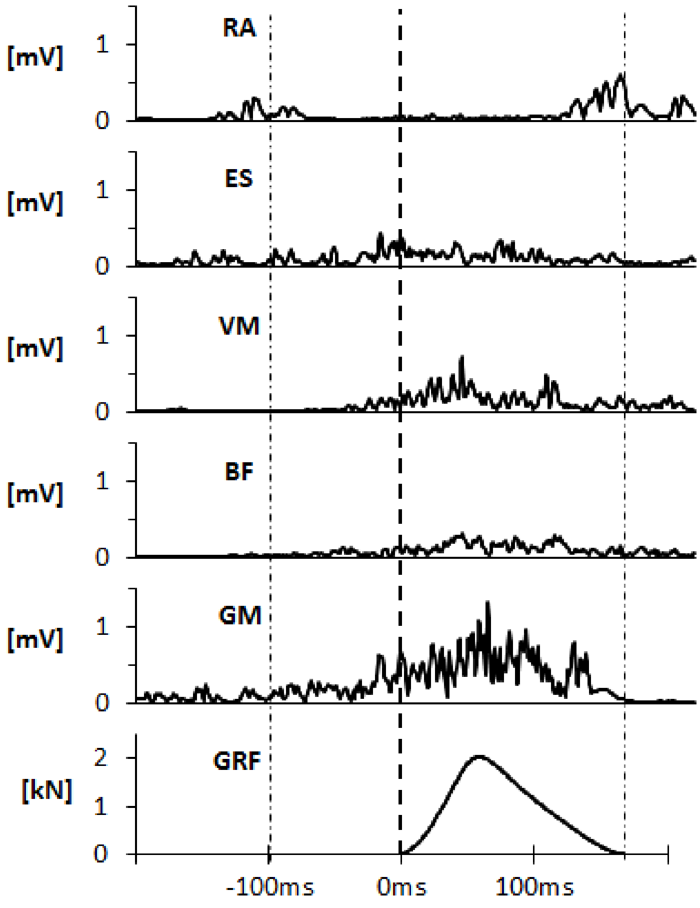

Figure 5: Illustration of synchronized ground reaction force (GRF) and electromoygraphic signals of one subject recorded during drop jumps on unstable surface (average of 3 trials). RA = m. rectus abdominis, ES = m. erector spinae, VM = m. vastus medialis, BF = m. biceps femoris, GM = m. gastrocnemius medialis. Dashed lines indicate the time intervals for preactivation and ground contact phase.

In order to examine knee motion strategies in the frontal plane, two-dimensional knee joint kinematics were assessed with a motion capture and analysis software (Simi Motion 7.3, Simi Reality Motion Systems GmbH, Unterschleissheim, Germany) using a high-speed camera (240 Hz; A602fc, Basler AG, Ahrensburg Germany). The camera was placed perpendicular to the frontal plane of the participants. Retroflective markers were located on the anterior superior iliac spine, patella, malleolus medialis, and the second metatarsal bone of the dominant leg. Knee valgus motion was calculated by analyzing the frame before ground contact and the frame with the knee being positioned in maximum medial (valgus) angle (Myer et al. 2012). According to Myer et al. (2012), knee valgus motion was defined as the horizontal displacement between the knee coordinates of the two frames. All frontal plane measures were analyzed using the mean of 3 drop jump trials.

4.3.3.5 Assessment of trunk and leg muscle activity

EMG activity of 2 trunk muscles (m. rectus abdominis, m. erector spinae lumbalis) and 3 leg muscles (m. vastus medialis, m. biceps femoris, m. gastrocnemius medialis) were measured using circular bipolar surface electrodes (Ambu®, type Blue Sensor P-00-S/50, Ag/AgCl, diameter: 13 mm, center-to-center distance: 25 mm, Ballerup, Denmark). The leg and trunk muscles were analyzed on the dominant side in terms of leg preference. Electrodes were positioned on the muscle bellies according to the European recommendations for surface electromyography (Hermens et al. 1999). The longitudinal axes of the electrodes were in line with the direction of the underlying muscle fibers. Inter-electrode resistance was kept below 5 kΩ by means of shaving, slightly roughening, degreasing, and disinfecting the skin. The EMG signals were amplified and recorded telemetrically (TeleMyo 2400T DTS, Noraxon®, Scottsdale, AZ, USA) to a computer at a sampling frequency of 1,500 Hz. After removal of heart muscle electrical activity artifacts from the trunk muscle signals by combining adaptive filter methods with a pattern recognition mode (Prieske et al. 2013), the filtered (10-750 Hz bandwidth), full-wave rectified and integrated EMG (iEMG) signals were averaged for 3 drop jump trials triggered on the instant of ground contact. Mean average voltage (MAV; defined as iEMG normalized relative to the integration time) was calculated for the preactivation (integration time: 100 ms interval prior to onset of ground contact) and ground contact phase (integration time: interval from onset to offset of ground contact) (Figure 1). MAV values of trunk and leg muscles were normalized to preactivation MAV values of landing on a stable surface (Prieske et al. 2013). Therefore, 3 landing trials were performed on the force plate. The procedure during the landing task was similar to the drop jump task. Participants stood on a platform with hands akimbo. Subjects had to initially step off the platform, drop down from a height of 40 cm and land with both feet on the force plate.

4.3.3.6 Statistical analyses

Data are presented as group mean values ± standard deviation (SD). After normal distribution (i.e., Kolmogorov-Smirnov-Test) was examined, associations of neuromuscular performance measures between trunk and leg during drop jumps on stable and unstable surfaces were assessed using Pearson product-moment correlation coefficients. Since associations were not affected by factor sex, correlation analyses were pooled for men and women. Associations are reported by their correlation coefficient r, level of significance, and the amount of variance explained (r^2). Values of $r \leq .69$ indicate a small, $.70 \leq r \leq .89$ indicate a medium, and $r \geq .90$ indicate a large size of correlation (Vincent 1995). Further, the independent samples t-Test was used to identify sex-specific differences. The significance level was set at $p < 0.05$. All analyses were performed using Statistical Package for Social Sciences (SPSS) version 22.0.

4.3.4 Results

Means and SDs are presented in Table 1 for variables of trunk muscle strength, drop jump performance, and lower limb kinematics.

4.3.4.1 Trunk muscle strength, drop jump performance, and lower limb kinematics

Statistically significant positive correlations were detected between PIT of the trunk extensors but not flexors and variables of drop jump performance (i.e., drop jump height, drop jump performance index) and lower limb kinematics (i.e., knee valgus motion) on stable and unstable surfaces (Table 7). Respective r-values ranged from -.48-.64 ($p < 0.05$) under stable and from -.45-.66 ($p < 0.05$) under unstable conditions. In other words, participants with high trunk extensor PIT showed higher jump height, higher performance index, and lower knee valgus motion during drop jumps compared to participants with low trunk extensor PIT, irrespective of surface condition. Values for r^2 indicated an explained variance of 23-41 % (stable surface) and 21-43 % (unstable surface).

Table 7: Correlation between peak isokinetic torque (PIT) of trunk flexors/extensors and performance measures during drop jumps by surface condition.

	Drop jump height		**Drop jump performance index**		**Knee valgus motion**	
	Stable	**Unstable**	**Stable**	**Unstable**	**Stable**	**Unstable**
PIT trunk flexors	.32	.32	.23	.28	.08	.14
PIT trunk extensors	.64**	.66**	.50**	.60**	-.48*	-.45*

*$p < 0.05$, **$p < 0.01$

4.3.4.2 Trunk and leg muscle activity

Statistically significant positive correlations were observed between trunk (i.e., m. rectus abdominis, m. erector spinae) and leg muscle activity (i.e., m. vastus medialis, m. biceps femoris, m. gastrocnemius medialis) for preactivation and ground contact intervals during drop jumps on stable and unstable surfaces (Table 8).

Table 8: Correlation between trunk and leg muscle activation during drop jumps by time interval and surface condition.

	m. rectus abdominis				**m. erector spinae**			
	Preactivation		**Ground contact**		**Preactivation**		**Ground contact**	
	Stable	**Unstable**	**Stable**	**Unstable**	**Stable**	**Unstable**	**Stable**	**Unstable**
m. vastus medialis								
Preactivation	.37	.46*	.09	.02	.24	.47*	.05	.15
Ground contact	.45*	.30	.35	.52**	.07	.24	.14	.18
m. biceps femoris								
Preactivation	.35	.25	-.01	.01	.10	.10	-.20	.01
Ground contact	.46*	.46*	.16	.19	.24	.51*	.30	.27
m. gastrocnemius medialis								
Preactivation	.18	.16	.17	-.15	.28	.05	.25	-.07
Ground contact	-.04	-.03	.52**	.68**	.02	.23	.45*	.45*

*$p < 0.05$, **$p < 0.01$

Regarding trunk muscle activity during the preactivation phase, respective *r*-values ranged from .45-.46 ($p < 0.05$) under stable conditions and from .46-.51 ($p < 0.05$) under unstable conditions. Values for r^2 indicated an explained variance of 20-21 % (stable surface) and 21-26 % (unstable surface).

In terms of trunk muscle activity during ground contact phase, respective *r*-values ranged from .45-.52 ($p < 0.05$) under stable conditions and from .45-.68 ($p < 0.05$) under unstable conditions. Values for r^2 indicated an explained variance of 20-27 % (stable surface) and 20-46 % (unstable surface).

4.3.5 Discussion

This is the first study that examined the role of the trunk during jump tasks on stable and unstable surfaces on a behavioral and neuromuscular level. The purpose of the present study was to investigate potential associations between trunk muscle strength, drop jump performance, and lower limb kinematics. Additionally, correlations were also computed on a neuromuscular level between trunk and leg muscle activity during drop jumps on stable and unstable surfaces. The main findings of this study can be summarized as follows: (1) significant but small associations were detected between trunk extensor PIT and drop jump performance/lower limb kinematics under stable and unstable surface conditions, (2) significant but small correlations were found between trunk and leg muscle activity on stable und unstable surfaces.

4.3.5.1 Trunk muscle strength, drop jump performance, and lower limb kinematics

Significant but small correlations were found between variables of trunk muscle strength, drop jump performance (i.e., drop jump height, drop jump performance index), and lower limb kinematics (i.e., knee valgus motion) on stable ($-.48 \leq r \leq .64$) and unstable surfaces ($-.45 \leq r \leq .66$). First, this is in line with the literature regarding studies that investigated associations between measures of trunk muscle strength and athletic performance (Nesser et al. 2008, Okada et al. 2011, Sharma et al. 2012). For instance, Okada et al. (2011) found significant but small correlations between variables of isometric trunk muscle endurance (i.e., trunk extension/flexion; left/right bridge) and performance in single leg squat on stable surface (all $r = .50$) in young recreational athletes. Further, Nesser et al. (2008) reported *r*-values ranging from .40-.59 between isometric trunk muscle endurance (i.e., extension/flexion/

lateral endurance) and countermovement jump height on stable surface in male football players. Lastly, small correlations (i.e., .48 ≤ *r* ≤ .68) have been reported between performance in dynamic trunk muscle strength tests (i.e., double leg lowering) and jump performance (e.g., squat jump height, countermovement jump height, block jump height) on stable surface in volleyball players (Sharma et al. 2012). However, in the aforementioned studies, tests of trunk muscle endurance and trunk stability were performed under submaximal isometric or slow-moving conditions whereas we conducted maximal isokinetic (dynamic) trunk muscle testing. Of note, it was observed that larger motor units are progressively recruited when movement intensity (e.g., force level) increased (Henneman 1957, Milner-Brown et al. 1973, Desmedt and Godaux 1977). Consequently, it can be argued that trunk muscle endurance tests primarily activate slow-twitch muscle fibers due to the submaximal character of muscle actions, whereas strength and power tests involve both slow- and fast-twitch muscle fibers due to maximal activation levels. Thus, the applied trunk muscle tests in the aforementioned studies (Nesser et al. 2008, Okada et al. 2011, Sharma et al. 2012) may not be adequate to illustrate the importance of trunk muscle strength for athletic performance because many sports-related movements (e.g., jumping) require maximal and explosive force/torque production.

Second, the present findings of a significant relationship between trunk extensor PIT and knee valgus motion (-.45 ≤ *r* ≤ -.48) support the results of a recently published study. In fact, Jamison et al. (2013) observed a significant but small association (*r* = .49) between trunk muscle activation and knee abduction moments during run-to-cut maneuvers on stable surface in young healthy subjects. However, to our knowledge, ours is the first study that investigated the association between maximum isokinetic trunk muscle torque and lower limb kinematics (i.e., knee valgus motion).

Previously, it has been shown that trunk muscle activity was maintained whereas maximal performance output (i.e., jump height, force) decreased (Prieske et al. 2013, Saeterbakken and Fimland 2013) during lower extremity exercises (i.e., drop jumps, squats) on unstable compared to stable surfaces. Moreover, trunk muscle activity even increased with instability when the same absolute load was used during squat exercises (Anderson and Behm 2005, Bressel et al. 2009). This might indicate that the trunk is particularly important during jump performance on unstable surfaces. However, in the present study, similar relationships were found between maximal isokinetic trunk muscle torque and drop jump performance under stable and unstable conditions. Our results extend previous findings of Keogh et al. (2010) who investigated the impact of surface condition on associations between isometric trunk muscle endurance (i.e., trunk extension/flexion; left/right bridge) and maximal upper extremity strength (i.e., seated shoulder dumbbell press). The authors observed a significant but small correlation (r = .48) between trunk muscle endurance of the flexors and maximal strength of the shoulder during a seated dumbbell press on a Swiss ball. With reference to the findings of Keogh et al. (2010) and our own results, it seems reasonable to argue that surface condition does not affect associations between measures of trunk muscle strength and athletic performance.

In the present study, significant relationships were found only between PIT of trunk extensor muscles and drop jump performance as well as lower limb kinematics. However, due to the small magnitude of the correlations, it seems plausible to argue that strengthening of trunk muscles has only limited effects on jump height, performance index, and knee valgus motion during drop jumps on stable and unstable surfaces. In fact, this is supported by Jamison et al. (2012) who investigated the effects of a short-term trunk stabilization training on measures of trunk muscle strength and leg muscle performance in healthy males. Six weeks of training resulted in improved trunk muscle strength (i.e., trunk muscle endurance), but not in long jump distance. Further, in terms of lower extremity biomechanics, knee valgus moments during a run-to-cut maneuver did not change with trunk stabilization training. These findings together with the results of the present study could be beneficial for coaches and therapists in terms of the development and application of effective training programs during preseason and in-season conditioning as well as during prevention of sport injuries.

4.3.5.2 Trunk and leg muscle activity

It is well known that athletic function is often produced by kinetic chains, a coordinated activation of body segments that places optimum velocity with the optimum timing to produce the desired athletic task (Kibler et al. 2006). In this regard, Kibler et al. (2006) underlined the importance of trunk muscle activation to enable proximal to distal force generation patterns that propel and protect distal joints. In fact, prior activation of proximal muscle groups (e.g., m. erector spinae) may produce increased levels of muscle activation in the extremities which finally results in better jump performance (van Ingen Schenau et al. 1987). Further, during voluntary hip flexion, abduction, and extension tasks, Hodges and Richardson (1997) showed shorter reaction time intervals from visual stimulus to onset of EMG activity in several trunk muscles as compared to respective prime movers. This indicates that trunk muscles were activated prior to the prime movers in each of the above mentioned movement directions. The authors concluded that this control strategy provides trunk stability during lower limb movements. These results illustrate that higher levels of trunk muscle activity prior to and during performance can also increase levels of muscle activation in the extremities. In accordance with the findings regarding the relationship between trunk muscle strength and drop jump performance/lower limb kinematics, significant but small associations were found fortrunk and leg muscle activities ($.45 \leq r \leq .68$) during drop jumps, irrespective of surface condition. Although correlation coefficients of cross-sectional studies do not conclusively allow for cause-and-effect relations, our findings imply that these capacities are independent of each other and may thus have to be tested and trained complementarily. In other words, training induced adaptations in trunk muscle activation levels will not necessarily be transferred to limb muscle activation during jumping and/or vice versa.

4.3.6 Conclusions

Our behavioral data indicated statistically significant associations between trunk extensor PIT and performance during jumping. Our neuromuscular data revealed statistically significant relationships between trunk and leg muscle activity during drop jumps on stable and unstable surfaces. However, given that the calculated correlation coefficients were small, it seems plausible to argue that irrespective of surface condition, the trunk plays only a minor role for drop jump performance (i.e., drop jump height, drop jump performance index) and lower limb kinematics (i.e., knee valgus motion). Consequently, trunk muscle strengthening may have only limited effects on drop jump performance.

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4.4 Study 4

EFFECTS OF CORE STRENGTH TRAINING USING STABLE VERSUS UNSTABLE SURFACES ON PHYSICAL FITNESS IN ADOLESCENTS: A RANDOMIZED CONTROLLED TRIAL

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4.4.1 Abstract

It has been demonstrated that core strength training is an effective means to enhance trunk muscle strength (TMS) and proxies of physical fitness in youth. Of note, cross-sectional studies revealed that the inclusion of unstable elements in core strengthening exercises produced increases in trunk muscle activity and thus provide potential extra training stimuli for performance enhancement. Thus, utilizing unstable surfaces during core strength training may even produce larger performance gains. However, the effects of core strength training using unstable surfaces are unresolved in youth. This randomized controlled study specifically investigated the effects of core strength training performed on stable surfaces (CSTS) compared to unstable surfaces (CSTU) on physical fitness in school-aged children. Twenty-seven (14 girls, 13 boys) healthy subjects (mean age: 14 ± 1 years, age range: 13-15 years) were randomly assigned to a CSTS (n = 13) or a CSTU (n = 14) group. Both training programs lasted 6 weeks (2 sessions/week) and included frontal, dorsal, and lateral core exercises. During CSTU, these exercises were conducted on unstable surfaces (e.g., TOGU© DYNAIR CUSSIONS, THERA-BAND© STABILITY TRAINER).Significant main effects of Time (pre vs. post) were observed for the TMS tests (8-22 %, *f* = 0.47-0.76), the jumping sideways test (4-5 %, *f* = 1.07), and the Y balance test (2-3 %, *f* = 0.46-0.49) Trends towards significance were found for the standing long jump test (1-3 %, *f* = 0.39) and the stand-and-reach test (0-2 %, *f* = 0.39). We could not detect any significant main effects of Group. Significant Time x Group interactions were detected for the stand-and-reach test in favor of the CSTU group (2 %, *f* = 0.54). Core strength training resulted in significant increases in proxies of physical fitness in adolescents. However, CSTU as compared to CSTS had only limited additional effects (i.e., stand-and-reach test). Consequently, if the goal of training is to enhance physical fitness, then CSTU has limited advantages over CSTS.

4.4.2 Background

Core muscle strength is an important prerequisite for several sport (e.g., track and field, climbing, soccer), and everyday activities (e.g., sitting, standing, walking in an upright position). Anatomically, the core can be described as a muscular box with the abdominals in the front, paraspinals and glutes in the back, the diaphragm as the roof, and the pelvic floor and hip girdle musculature as the bottom (Akuthota et al. 2008). Functionally, the core can be thought of as the kinetic link that facilitates the transfer of torques and angular momentum between the lower and upper extremities that is of vital importance for sport-specific and everyday activities in different age groups (Kibler et al. 2006). In fact, data from a cross-sectional study indicate significant relationships between variables of core muscle strength, sprint, throw, and jump performance in young healthy individuals (Nesser et al. 2008; Okada et al. 2011). With reference to these findings, it seems plausible to argue that core strength training may have the potential to improve core muscle strength as well as health-related (i.e., strength, flexibility) and skill-related (i.e., balance, coordination, speed) components of physical fitness in youth. To the best of our knowledge, there is only one study available that investigated the impact of a 6-week core conditioning program in healthy untrained school-aged children (Allen et al. 2013). As a result, the authors found significant performance enhancements in different trunk muscle endurance tests.

Performance of several everyday and sports-related activities occurs on relatively unstable surfaces (e.g., walking on cobblestone pavement, jumping on uneven natural turf, landing on sand during beach-volleyball, kicking a ball while being impeded by an opponent). Thus, according to the concept of training specificity, training must attempt to closely address the demands of these activities. In this regard, Behm and Colado-Sanchez (2013) propagated strength training using unstable surfaces and/or devices for performance enhancement and musculoskeletal health in youth and old adults. In a recent study, Granacher et al. (2013) conducted a 9 week progressive core strength training on unstable surfaces in community-dwelling old adults (age: 63-80 years). Compared to a passive control group, the intervention group significantly improved measures of trunk muscle strength (TMS), spinal mobility, functional mobility, and dynamic balance. It was concluded that core strength training conducted on unstable surfaces is a feasible and effective exercise program for attenuating age-related performance decrements in old adults. However, in this study core strength training has been conducted on unstable surfaces only. Thus, this study was not able to elucidate the potential additive effect of core strength training using unstable surfaces as compared to core strength training on stable surfaces. Of note, the application of unstable surfaces during youth strength training might be particularly beneficial because balance and coordination are not yet fully developed in school-aged children (Riach and Hayes 1987). Furthermore, the inclusion of unstable elements in strength training exercises leads to substantial force decrements while at the same time overall muscle activity appears to remain unchanged (Anderson and Behm 2004). However, there is evidence in the literature (Faigenbaum et al. 1999) that reduced loads combined with high repetitions still represent a sufficient training stimulus in youth which is why strength training performed on unstable surfaces seems to be well-suited for the promotion of health-related and skill-related components of physical fitness in youth. However, as of now there is no study available that compared the effects of core strength training performed on stable surfaces (CSTS) with core strength training performed on unstable surfaces (CSTU) in youth. In an attempt to fill this void in the literature, we specifically studied the effects of CSTU versus CSTS on health-related and skill-related components of physical fitness in youth.

Based on study findings mentioned above (Behm and Colado Sanchez 2013; Okada et al. 2011; Faigenbaum et al. 1999; Hibbs et al. 2008; Nesser et al. 2008; Allen et al. 2013; Hoshikawa et al. 2013), we hypothesized that participants performing CSTU as compared to CSTS will show larger improvements in physical fitness tests (i.e., strength, speed, flexibility, coordination, balance) following training. Of note, training induced gains in strength, speed, flexibility, coordination, and balance are of vital importance for sports performance, everyday activities, and injury prevention.

4.4.3 Methods

To test our hypothesis, adaptations following CSTS as compared to CSTU were assessed using a parallel group randomized controlled study design that included pre- and post-testings and core strength training in between. The training period lasted 6 weeks to induce training-related changes in measures of strength, speed, flexibility, coordination, and balance. These health-related (i.e., strength, flexibility) and skill-related (i.e., balance, coordination, speed) components of physical fitness (Caspersen et al. 1985) were assessed using physical fitness tests (i.e., Bourban TMS test, standing long jump test, 20-m sprint test, stand-and-reach test, jumping sideways test, Emery balance test, Y balance test).

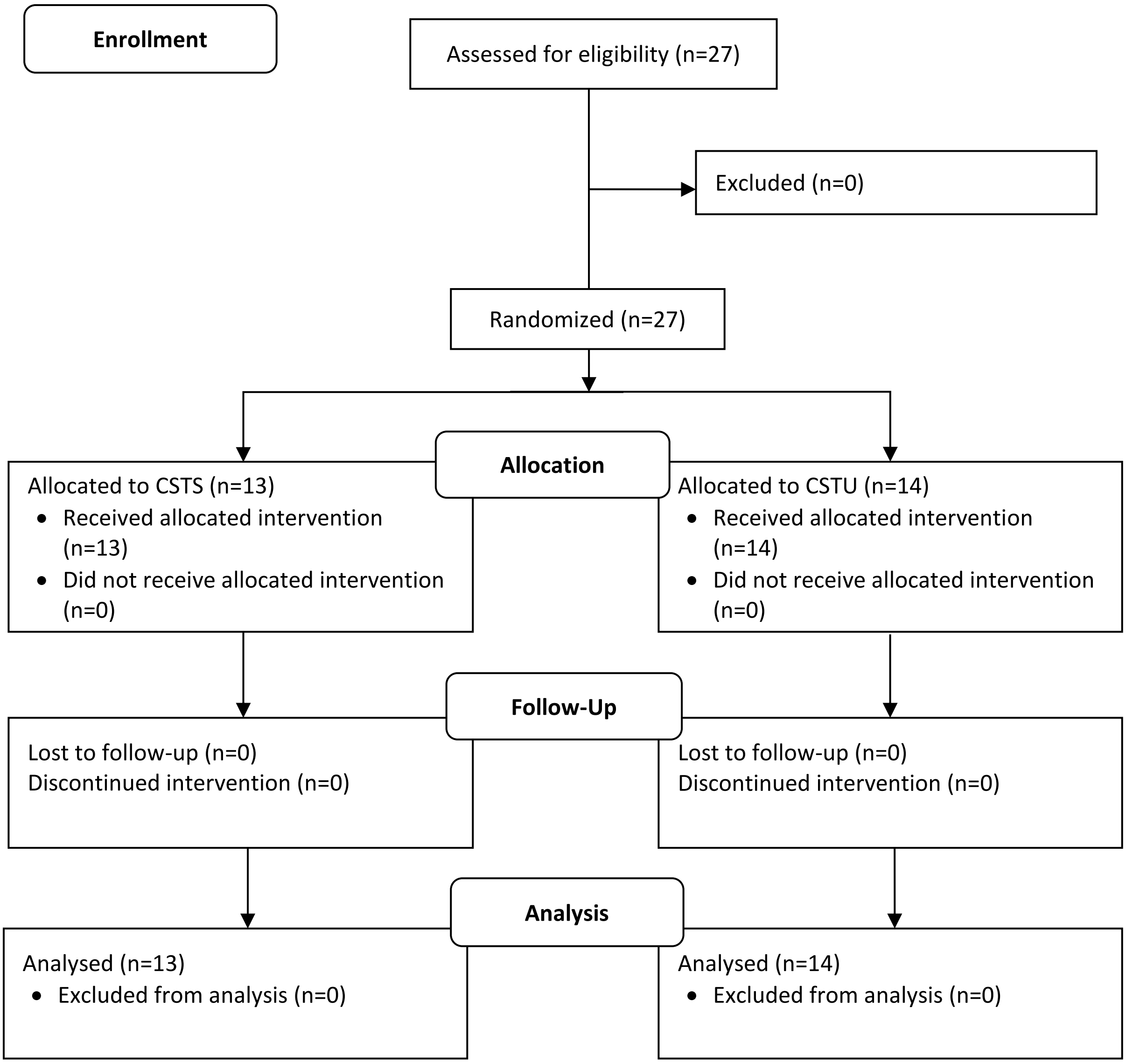

Figure 6: Flow chart of the progress through the phases of the study according to the CONSORT statements.

4.4.3.1 Participants

Twenty-seven healthy boys and girls participated in this study after the experimental procedures were explained. Figure 6 shows a flow chart of the study design. An a priori power analysis (Faul et al. 2007) with an assumed Type I error of 0.05 and a Type II error rate of 0.20 (80% statistical power) was calculated for measures of trunk muscle strength (Hoshikawa et al. 2013) and revealed that 13 participants per group would be sufficient to observe medium “Time × Group” interaction effects. Study participants were recruited from local sports clubs between May and June 2014. All participants can be classified as physically active according to the Freiburg questionnaire of everyday and sports-related activities (Frey et al. 1999). All subjects were advised not to decrease or increase their daily sport activities over the course of the study. Characteristics of the study population are described in Table 9.

Table 9: Characteristics of the study participants.

Characteristic	**Core strength training on stable surfaces (n = 13)**		**Core strength training on unstable surfaces (n = 14)**		
	M	**SD**	**M**	**SD**	***p*-value**
Age (years)	13.7	0.6	13.8	0.9	.758
Body height (cm)	168.6	9.7	169.6	9.3	.796
Body mass (kg)	53.1	9.6	51.4	7.3	.602
Body mass index (kg/m^2)	18.6	2.4	17.8	1.5	.309
Sex (f/m)	7/6	7/6	7/7	7/7	
Physical activity (h/week)	7.1	2.9	6.8	2.4	.721
Leg length left (cm)	79.9	6.5	78.7	4.6	.567
Leg length right (cm)	79.5	6.3	78.3	4.4	.575

Note. f = female; m = male; M = mean; SD = standard deviation.

All participants were eligible for inclusion in this study because they had no history of musculoskeletal, neurological or orthopedic disorders that might have affected their ability to perform physical fitness tests and core strength training. Further, none had previously participated in systematic strength or balance training. Subjects were randomly assigned to one of 2 intervention (i.e., CSTS or CSTU) using the method of randomly permuted blocks using Research Randomizer, a program published on a publicly accessible official website (www.randomizer.org). Two independent experimenter (JS, KK) generated the random allocation sequence, enrolled participants, and assigned participants to the intervention groups. Group 1 conducted a CSTS program under stable conditions whereas group 2 performed CSTU. Parents` and participants` informed consents were obtained before the start of the study. Ethical permission was given by the ethics committee of the University of Potsdam (submission No. 26/2014) and all experiments were conducted according to the latest version of the declaration of Helsinki. Written informed consent was obtained from the participant for publication of Figures 7a-c. A copy of the written consent is available for review by the Editor of this journal.

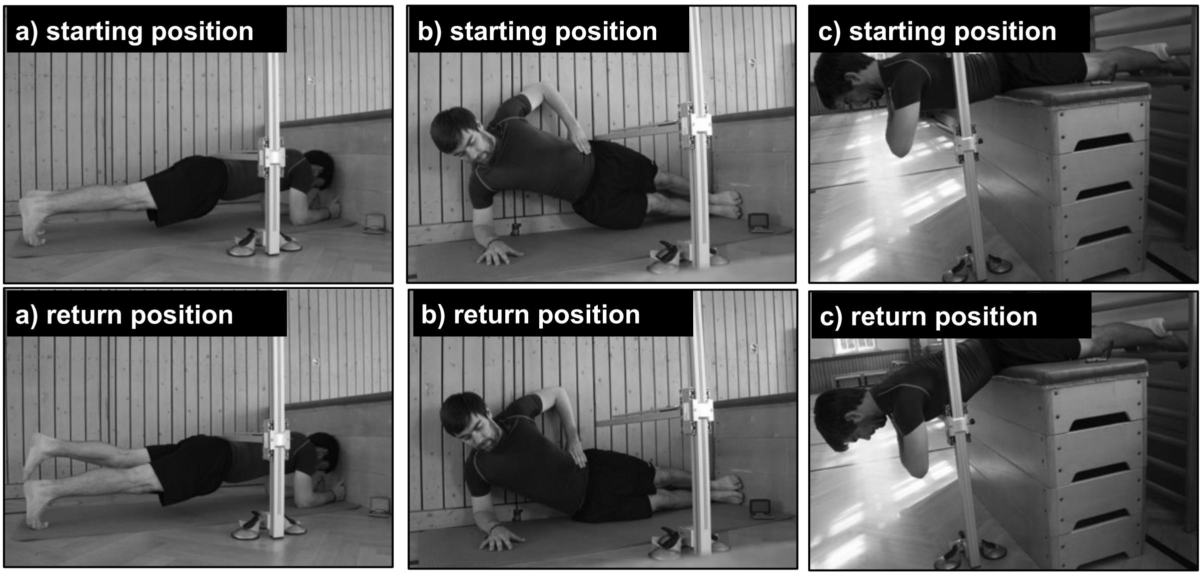

Figure 7: Schematic description of the Bourban trunk muscle strength test (a: the ventral trunk muscle chain test, b: the lateral trunk muscle chain test, c: the dorsal trunk muscle chain test).

4.4.3.2 Procedures

Core Strength Training

Both core strength training programs were supervised and conducted by 2 experienced physiotherapists. Thus, the participant-to-supervisor ratio was kept small for both intervention groups with 2 supervisors to 13 participants in the CSTS group and 2 supervisors to 14 participants in the CSTU group. The two programs were organized as circuit training with each instructor supervising 6-7 participants. Both training programs lasted 6 weeks and comprised 2 training sessions per week with a total of 12 training sessions for each intervention group. Each training session lasted 30 min, starting with a brief, standardized warm-up program mainly consisting of low-intensity core strength exercises to prepare the neuromuscular system for the training loads and ending with a cool-down program (i.e., dynamic stretching). During the main part of training, both groups mainly conducted the “big 3” exercises as described by McGill (2001). These include the curl-up, side bridge, and quadruped position. In other words, every single training session consisted of frontal, dorsal, and lateral core exercises. The only difference between the 2 intervention groups was that the CSTU protocol comprised core exercises that were conducted on unstable surfaces (i.e., TOGU©

DYNAIR PRO, SENSO, TOGU© REDONDO BALLS, TOGU© POWERBALLS, THERA-BAND© STABILITY TRAINER, THERA-BAND© EXERCISE BALL), whereas the CSTS program contained the same exercises on stable surface only. Table 10 illustrates a detailed description of the core exercises. The CSTU protocol has recently been published (Granacher et al. 2013).

Table 10: Description of the two core strength training programs.

The "big 3" core exercises	Core strength training on stable surfaces	Core strength training on unstable surfaces
Cross curl-ups	basic exercise position and execution of exercise: subjects were lying in supine position, hands folded in the neck, elbows pointed to the sides, knees in a flexed position, feet rested on a fitness mat; subjects curled-up until the scapulae left the fitness mat, subjects rotated to the left and right at a moderate movement velocity; progression during training: by increasing contraction time (see text), by lifting the feet up in the air at a 90° knee angle	basic exercise position and execution of exercise: same as during the stable condition; additionally, subjects were sitting on a Togu© Dynair cussion and each foot rested on a basketball; progression during training: by increasing contraction time (see text), by alternately extending the arms from behind the neck
Side bridge (both sides)	basic exercise position and execution of exercise: subjects were lying in a side position with knees flexed, the supporting shoulder superior to the respective elbow, the uninvolved arm held akimbo, and the supporting forearm flat on the fitness mat; subjects raised their hips until a straight line was reached from the knees up to the shoulders, subjects continuously raised and lowered their hips at a moderate movement velocity; progression during training: by increasing the number of repetitions (see text), by extending the legs so that a straight line was reached over the whole body, and by lifting the upper leg up in the air	basic exercise position and execution of exercise: same as during the stable condition; additionally, a Togu© Redondo ball with a diameter of 22 cm was placed underneath the subjects' knees; progression during training: by increasing the number of repetitions (see text), by placing a Togu© Redondo ball underneath the feet; by placing a basketball underneath the supporting forearm
Quadrupedal stance ("birddog exercise")	basic exercise position and execution of exercise: subjects started in a quadrupedal stance with both hands and knees flat on the surface; subjects lifted a leg and the contralateral arm in horizontal position; subjects alternately lifted and lowered their leg and contralateral arm at a moderate movement velocity; progression during training: by increasing the number of repetitions (see text)	basic exercise position and execution of exercise: same as during the stable condition; additionally, a basketball was placed underneath the supporting hand; progression during training: by increasing the number of repetitions (see text), by placing a Togu© Redondo ball with a diameter of 22 cm underneath the supporting knee; by additionally lifting the foot of the supporting leg off the floor

In general, participants always exercised in pairs so that one subject trained and the other one provided support (i.e., motivation, spotting). Training intensity was progressively and individually increased over the 6-week training program by modulating lever lengths, movement velocity (isometric, dynamic), range of motion (i.e., CSTS and CSTU) and the level of instability (i.e., CSTU). During training weeks 1-2, participants of the CSTS and the CSTU performed the "big 3" exercises with 3 sets per exercise and 40 s contraction time (isometric condition) or 20 repetitions (dynamic condition). During training weeks 3-4, contraction times and repetitions were increased to 45 s or 23 repetitions. During training weeks 5-6, contraction times and repetitions were increased to 50 s or 25 repetitions. The rest between sets was similar to the respective contraction time (e.g., 40 s during weeks 1-2). An additional 2-3 min rest was provided between exercises.

Testing

All tests were performed in the respective school gyms during official physical education lessons using standardized test protocols. Prior to pre- and post-tests, all participants underwent a standardized 5-minutes warm-up which consisted of bipedal and monopedal balance, submaximal plyometric, and skipping exercises. Thereafter, physical fitness tests (i.e., secondary outcome measures: Emery balance test, Y balance test, stand-and-reach test, 20-m sprint test, jumping sideways test, standing long jump test; primary outcome measures: Bourban TMS test) were assessed. This sequence of measurements was applied to keep the effects of neuromuscular fatigue minimal during pre- and post-testing.

Bourban TMS Test

The Bourban TMS test assesses core strength endurance of ventral, lateral, and dorsal trunk muscle chains. Tests were applied in randomized order with a 10 min rest between the tests. During the ventral trunk muscle chain test, subjects were in prone bridge position on their elbows and toes (Figure 7a). Legs were extended, elbows shoulder-widths apart, and forearms lay flat on a fitness mat. In this test position, the glenohumeral joint, the greater trochanter, and the lateral malleolus were located on a straight line. An adjustable alignment device was constructed that consisted of a stable vertical pole with two vertically adjustable horizontal rods (Bourban et al. 2001). While in the bridged position, the lower horizontal reference rod of the alignment device was moved into contact with the participant's lower back at the level of the iliac crests and was then fixed at this position. After visual inspection of the subjects´ starting position, they were asked to lift their feet alternately for 2-5 cm according to the beat of a metronome (1 s per foot). Before the test started, subjects were instructed to remain in contact with the horizontal reference rod for as long as possible. Warnings were given when subjects lost touch to the horizontal rod. The test was terminated when participants failed to remain in contact with the reference rod for the third time. Contact time until test termination was taken as dependent variable and used for further analysis. According to recommendations regarding absolute reliability (Stokes), the ventral test can be classified as reliable with a coefficient of variation of 14.1 % (Tschopp et al. 2001). During the lateral trunk muscle chain test, subjects were in a side bridge position with legs extended, the upper foot placed on top of the lower foot, and the supporting shoulder superior to the respective elbow (Figure 7b). The supporting forearm was placed flat on the fitness mat and the uninvolved arm was held akimbo. The test was performed in randomized order for the right and left side. Subjects raised their hips until a straight line was reached from the ankles up to the shoulders. While in the side bridged position, the lower horizontal reference rod of the alignment device was fixed at the height of the superior iliac crest. After visual inspection of the subjects´ starting position, participants continuously raised and lowered their hips to the beat of a metronome (2 s per lowering and lifting cycle). They were not allowed to unload their body mass on the fitness mat during the lowering phase. Warnings were given when subjects lost touch to the horizontal rod or when they unloaded their body mass on the fitness mat. The test was terminated when participants received the third warning. Time until test termination was taken as dependent variable and used for further analysis. According to recommendations regarding absolute reliability (Stokes 1985), the lateral test can be classified as reliable with a coefficient of variation (CoV) of 14.6 % (Tschopp et al. 2001). During the dorsal trunk muscle chain test, subjects lay prone on a wooden box while maintaining an unsupported trunk (from the upper border of the iliac crest) (Figure 7c). Participants held their arms across the chest, hands rested on the shoulders, legs were extended, and the feet were firmly fixed in wall bars. The horizontal position (0 °) was controlled using a mechanical goniometer. While in this position, the upper horizontal reference rod of the alignment device was fixed at the level of a thoracic spinal process. Thereafter, the subject lowered the trunk by 30 ° which was again controlled by a mechanical goniometer. While in this position, the lower horizontal reference rod of the alignment device was fixed at the level of the sternal angle. After visual inspection of subjects´ starting position, participants continuously raised and lowered their trunk to the beat of a metronome (2 s per lowering and lifting cycle). The test was terminated when participants failed to reach the upper horizontal rod for the third time. Time until test termination was taken as dependent variable and used for further analysis. According to recommendations regarding absolute reliability (Stokes 1985), the dorsal test can be classified as reliable with a CoV of 11.7 % (Tschopp et al. 2001).

Standing Long Jump Test

The standing long jump test has been considered a general index of muscular fitness in youth (Castro-Pinero et al. 2010). Before the test started, subjects were instructed to stand with both feet right behind a starting line and to jump as far as possible. Subjects were allowed to use arm swing during the test. Three trials were performed with a 2 min rest between trials. The best trial in terms of maximal distance from the starting line to the landing point at heel contact was used for statistical analysis. Measurements were taken to the nearest cm using a tape measure. The standing long jump test has been reported to be reliable with a CoV of 2.4 % (Markovic et al. 2004).

20-m Sprint Test

Maximum effort sprints were assessed from a stationary start. Subjects were instructed to stand with one foot right behind the starting line and to accelerate at maximum effort to the finish line. The best out of 3 trials (i.e., minimal sprint time) with a 2 min rest between trials was used for further data analysis. Time was taken with a stop watch to the nearest 1/100 s. Excellent test-retest reliability has been reported for the hand stopped 20-m sprint test with an intraclass correlation coefficient (ICC) of 0.90 (Bös et al. 2009).

Stand-and-Reach Test

Spinal and pelvic flexibility was tested using the stand-and-reach test. Subjects were instructed to begin the test in a standing position on an elevated platform with feet together. They were asked to bend over using their maximal range of motion. During the test, knees, arms, and fingers were fully extended. A tape measure was attached to the platform with 100 cm indicating the top level of the platform. Values >100 cm indicate that the person was able to reach beyond the toes (i.e., good flexibility). Values <100 cm indicate that the person was not able to reach the toes (i.e., limited flexibility). The maximum reach distance was taken as dependent variable. Two trials with a 1 min rest between trials were performed. Excellent test-retest reliability has been reported for the stand-and-reach test with an ICC of 0.94 (Bös et al. 2009).

Jumping Sideways Test

The jumping sideways test evaluates motor coordination under time pressure (Oberger et al. 2010). Subjects were instructed to jump as many times as possible over a period of 15 s with both legs together back and forth across a strip of wood that was attached to a mat (50 × 100 cm). The number of jumps completed without touching the strip and without stepping off the mat was taken as dependent variable. Two trials with a 2 min rest between trials were performed and the mean of the 2 trials was taken for further analysis. Excellent test-retest reliability has been reported for the jumping sideways test with an ICC of 0.89 (Bös et al. 2009).

Emery Balance Test

The Emery balance test was conducted barefooted in single leg stance on an Airex balance pad. Eyes were closed and both legs were tested (Emery et al. 2005). For experimental testing, participants were asked to stand as stable as possible with the knee of the weight-bearing limb flexed at 30 °. The non-weight-bearing limb was flexed 45 ° at the knee and hands were placed on hips. Using a stopwatch, time was stopped upon loss of balance to the nearest 1/100 of a second and used as dependent variable. Loss of balance included removal of one hand from the hip, touching the balance pad or floor with the non-weight-bearing foot, movement of the weight-bearing foot from its original position on the balance pad, movement of the balance pad from its original position during the balance test, or when eyes were opened (Emery et al. 2005). Three trials were completed on each leg with 15 s rest between trials. The best trial in terms of maximum standing time was taken for further analysis. Adequate test-retest reliability has been reported for the Emery balance test with an ICC of 0.59 (Emery et al. 2005).

Y Balance Test

The lower quarter Y balance test is a dynamic test that requires subjects to maintain single leg stance while reaching as far as possible with the contralateral leg in 3 different movement directions (i.e., anterior, posteromedial, posterolateral) (Plisky et al. 2006). For this purpose, a grid consisting of 3 lines was constructed on a gym floor using a mechanical goniometer and adhesive tape measure. The 2 posterior lines extended from the centre of the grid and were positioned 135 ° from the anterior line with 45 ° between the two posterior lines. Each line was marked in 5 mm increments for measurement purposes. Before the test started, participants' length of the right and left leg were assessed in supine lying position by measuring the distance from the anterior superior iliac spine to the most distal aspect of the medial malleolus. Further, subjects practiced 6 trials per reach direction on each foot to get familiarized with the testing procedures. All trials were conducted barefooted. According to Plisky et al. (2006), subjects always started with the right foot placed at the centre of the grid and the left leg reaching in anterior direction as far as possible, lightly touching the farthest point possible on the line with the most distal part of the reach foot. Participants then returned to a bilateral stable stance position. After 3 reaches, the left foot was placed at the centre of the grid and the right leg maximally reached in anterior direction. Thereafter, the same test procedure was conducted for the posteromedial and the posterolateral reach. Between reaches, a rest of 15 s was allowed. The examiner manually measured the distance from the centre of the grid to the touch point and the results were documented after each reach. Trials were discarded and repeated if the participant (1) did not touch the line with the reach foot while maintaining weight bearing on the stance leg, (2) lifted the stance foot from the centre grid, (3) lost balance at any point during the trial, (4) did not maintain start and return positions for one full second, or (5) touched down the reach foot to gain considerable support. For further data analyses, the mean of 3 successful reaches was used for each leg in each of the 3 directions. According to Filipa et al. (2010), a composite score (CS) was calculated and taken as dependent variable using the following formula: CS = [(maximum anterior reach distance + maximum posteromedial reach distance + maximum posterolateral reach distance) / (leg length x 3)] x 100. Excellent test-retest reliability has been reported for the Y balance test in all 3 movement directions with ICC values ranging between 0.89 and 0.93 (Plisky et al. 2006).

4.4.3.3 Statistical analyses

Data are presented as group mean values and standard deviations. Given that we could not detect statistically significant differences between males and females ($p > 0.05$), data were pooled for males and females. A multivariate analysis of variance (MANOVA) was used to detect differences between study groups in all baseline variables. The effects of core strength training on variables of physical fitness were analysed in separate 2 (Group: CSTS, CSTU) × 2 (Time: pre, post) ANOVA with repeated measures on "Time". Bonferroni corrections were not necessary because our study design (2 × 2) did not demand multiple testing. When "Time × Group" interactions reached the level of significance, group-specific post hoc tests (i.e., paired t-tests) were conducted to identify the comparisons that were statistically significant. Additionally, the classification of effect sizes (f) was determined by calculating partial eta squared. According to Cohen (1988), $0.00 \leq f \leq 0.24$ indicate small effects, $0.25 \leq f \leq 0.39$ indicate medium effects, and $f \geq 0.4$ indicate large effects. The significance level was set at $p < 0.05$. Tendencies towards significance were denoted as $0.051 \leq p < 0.1$. All analyses were performed using Statistical Package for Social Sciences (SPSS) version 22.0.

4.4.4 Results

All subjects received treatment conditions as allocated. Twenty-seven participants completed the training program and none reported any training-related injury. Mean attendance rates at training sessions amounted to 81 % for the CSTS group and 83 % for the CSTU group. Table 11 describes pre and post intervention results for all outcome variables. Overall, there were no statistically significant differences in baseline values between the 2 intervention groups ($p > 0.05$).

4.4.4.1 Bourban TMS Test

The statistical analysis indicated significant main effects of "Time" for the ventral TMS test ($F_{1,25} = 14.51$, $p < 0.001$, $f = 0.76$) and the lateral left side TMS test ($F_{1,25} = 5.48$, $p < 0.05$, $f = 0.47$) (Figure 8a, b). Further, trends towards significant main effects of "Time" were observed for the dorsal TMS test ($F_{1,25} = 2.91$, $p = 0.10$, $f = 0.34$) and the lateral right side TMS test ($F_{1,25} = 2.86$, $p = 0.10$, $f = 0.34$). However, we could not detect a significant main effect of "Group" nor a "Time × Group" interaction (Table 11).

Table 11: Effects of the two core strength training programs on measures of physical fitness.

Variables	CSTS (n=13)					CSTU (n=14)					*p*-value (effect size *f*)		
	Pre		**Post**		**Δ (%)**	**Pre**		**Post**		**Δ (%)**	**Test**	**Group**	**Test x Group**
	M	**SD**	**M**	**SD**		**M**	**SD**	**M**	**SD**				
Strength													
Ventral TMS test (s)	65.5	37.0	74.7	39.3	14.0	67.9	34.1	83.1	28.7	22.4	.001 (.76)	.685 (.08)	.353 (.19)
Dorsal TMS test (s)	152.2	98.0	214.8	232.8	41.1	129.9	55.0	173.3	208.4	33.4	.100 (.34)	.572 (.11)	.758 (.06)
Lateral right side TMS test (s)	46.9	18.9	51.1	18.3	9.0	46.7	12.1	50.4	14.7	7.9	.103 (.34)	.937 (.00)	.913 (.00)
Lateral left side TMS test (s)	46.5	20.8	51.4	18.7	10.5	47.6	10.3	51.4	10.6	8.0	.028 (.47)	.921 (.00)	.746 (.06)
Standing long jump (cm)	187.6	47.4	189.6	39.0	1.1	201.1	20.0	207.1	18.8	3.0	.061 (.39)	.230 (.25)	.336 (.20)
Speed													
20-m sprint (s)	3.9	0.4	3.8	0.4	-2.6	3.7	0.2	3.7	0.2	0.0	.311 (.21)	.434 (.16)	.358 (.19)
Flexibility													
Stand-and-reach test (cm)	102.3	9.8	102.0	9.8	-0.3	99.6	8.7	101.5	8.2	1.9	.062 (.39)	.647 (.09)	.012 (.54)
Motor coordination under time pressure													
Jumping sideways (# of jumps)	45.8	7.9	49.5	5.0	8.1	48.9	4.0	53.8	4.4	10.0	.000 (1.07)	.068 (.38)	.477 (.14)

Balance												
Emery test on right leg (s)	9.0	4.8	7.9	3.9	-12.2	10.4	7.1	9.2	5.2	-11.5	.378 (.18)	.436 (.16)	.979 (.00)
Emery test on left leg (s)	10.3	7.2	10.5	7.9	1.9	8.9	4.6	10.7	6.2	20,2	.418 (.16)	.772 (.05)	.527 (.13)
Y balance test CS score on right stance leg (%)	119.9	12.0	123.3	10.9	2.8	122.2	10.3	124.5	8.7	1.9	.032 (.46)	.656 (.09)	.662 (.09)
Y balance test CS score on left stance leg (%)	120.2	12.2	123.4	11.7	2.7	122.5	10.3	124.5	8.2	1.6	.022 (.49)	.680 (.08)	.554 (.12)

Note. CS = composite score; CSTS = core strength training on stable surfaces; CSTU = core strength training on unstable surfaces; TMS = trunk muscle strength; # = number; the CS for the Y balance test was calculated according to the following formula: CS = [(maximum anterior reach distance + maximum posterior medial reach distance + maximum posterior lateral reach distance) / (leg length x 3)] x 100 (Filipa et al. 2010).

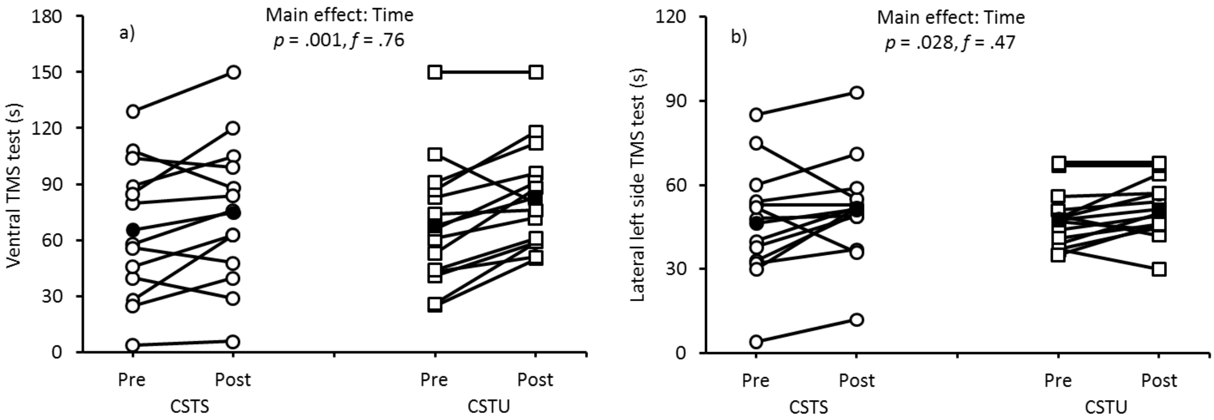

Figure 8: Individual and mean pre- and post-testing data for a) ventral trunk muscle strength (TMS) test and b) lateral left side TMS test by intervention group (CSTS, core strength training program using stable surfaces; CSTU, core strength training using unstable surfaces). Un-filled circles indicate individual data of the CSTS-group and filled circles indicate mean data of the CSTS-group. Unfilled squares indicate individual data of the CSTU-group and filled squares indicate mean data of the CSTU-group.

4.4.4.2 Standing Long Jump Test

A tendency towards a significant main effect of “Time” was found for the standing long jump test ($F_{1,\,25}$ = 3.85, p = 0.061, f = 0.39). Yet, no significant main effect of “Group” nor a “Time × Group” interaction were found (Table 11).

4.4.4.3 20-m Sprint Test

Our statistical calculations revealed no significant main effects of “Time” and “Group” and no significant “Time × Group” interaction for the 20-m sprint test (Table 11).

4.4.4.4 Stand-and-Reach Test

A trend towards a significant main effect of “Time” ($F_{1,\,25}$ = 3.83, p = 0.062, f = 0.39) but not of “Group” was detected for the stand-and-reach test (Figure 9a, Table 11). In addition, a significant “Time × Group” interaction was found ($F_{1,\,25}$ = 7.28, p = 0.012, f = 0.54). Post-hoc analysis revealed a significant increase in maximal reach distance from pre- to post-test in the CSTU group (Δ 2 %, p < 0.01).

4.4.4.5 Jumping Sideways Test

A significant main effect of “Time” ($F_{1,\,25}$ = 28.75, p < 0.001, f = 1.07) and a trend towards a significant main effect of “Group” ($F_{1,\,25}$ = 3.65, p = 0.068, f = 0.38) was found for the jumping sideways test. We could not detect a significant “Time × Group” interaction (Figure 9b, Table 11).

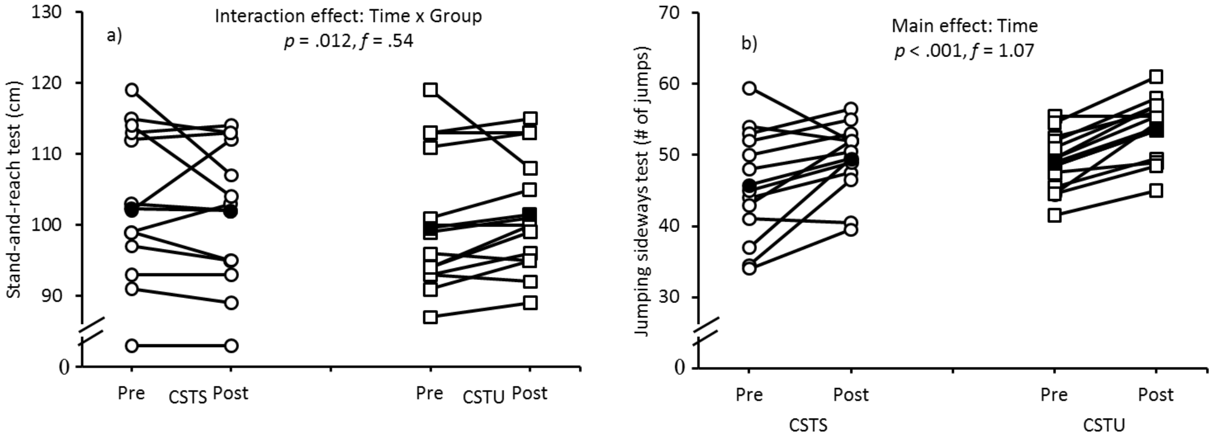

Figure 9: Individual and mean pre- and post-testing data for a) stand-and-reach test and b) jumping sideways test by intervention group (CSTS, core strength training program using stable surfaces; CSTU, core strength training using unstable surfaces). Unfilled circles indicate individual data of the CSTS-group and filled circles indicate mean data of the CSTS-group. Unfilled squares indicate individual data of the CSTU-group and filled squares indicate mean data of the CSTU-group.

4.4.4.6 Emery Balance Test

Our statistical analyses revealed no significant main effects of “Time” and “Group” and no significant “Time × Group” interactions for the Emery balance performed with the right and the left leg (Table 11).

4.4.4.7 Y Balance Test

Significant main effects of “Time” were investigated regarding the CS when performing the Y balance test on the right ($F_{1,\ 25}$ = 5.19, $p < 0.05$, f = 0.46) and the left leg ($F_{1,\ 25}$ = 5.98, $p < 0.05$, f = 0.49) (Figure 5a, b). Yet, no significant main effect of “Group” nor “Time × Group” interactions were investigated (Table 11).

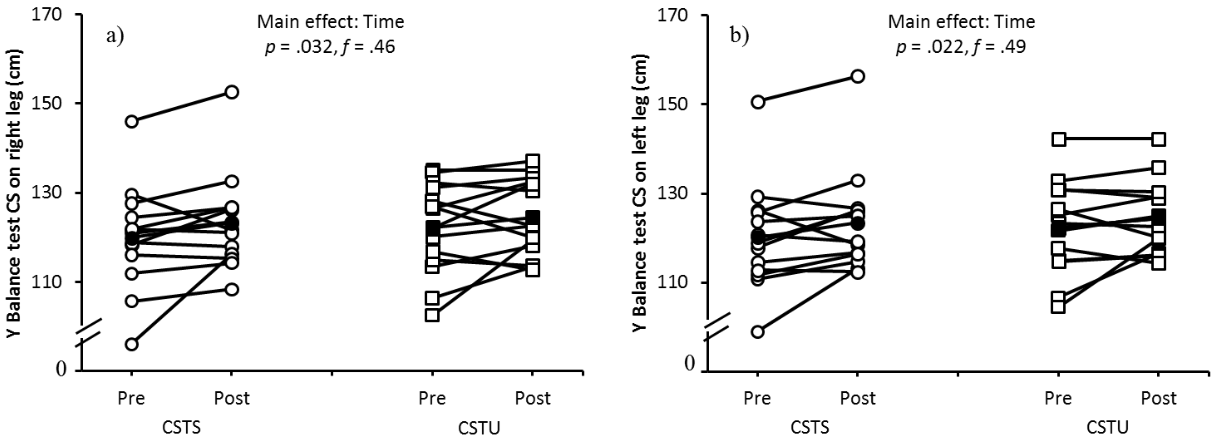

Figure 10: Individual and mean pre- and post-testing data for a) Y balance test composite score (CS) while standing on the right leg and b) Y balance test CS while standing on the left leg by intervention group (CSTS, core strength training program using stable surfaces; CSTU, core strength training using unstable surfaces). Unfilled circles indicate individual data of the CSTS-group and filled circles indicate mean data of the CSTS-group. Unfilled squares indicate individual data of the CSTU-group and filled squares indicate mean data of the CSTU-group.

4.4.5 Discussion

To the authors' knowledge, this is the first study that investigated the effects of CSTS compared to CSTU on health- and skill-related components of physical fitness in healthy youth. The main findings of this study were that (1) performance in physical fitness tests (i.e., Bourban TMS test, standing long jump test, stand-and-reach test, jumping sideways test, Y balance test) significantly improved in both intervention groups over the 6-week training period; (2) CSTU as compared to CSTS has only limited additional effects (i.e., stand-and-reach test) on physical fitness.

The present results are in accordance with the literature regarding the effects of core strength training on TMS and physical fitness in youth. Following 6 weeks of core strength training (e.g., low plank obliques, push-up jacks) conducted during physical education classes (1 session/week), Allen et al. (2013) found significant performance enhancements (f = 0.27-0.69) in 5 different trunk muscle endurance tests (i.e., Parallel Roman Chair Dynamic Back Extension, Prone Plank, Lateral Plank, Dynamic Curl-Up, Static Curl-up) in healthy untrained children with a mean age of 11 years. In a randomized controlled trial, Hoshikawa et al. (2013) investigated the effects of a combined core strength training (e.g., prone and side bridging on elbows) and soccer training (e.g., technical drills, interval runs) as compared to soccer training only (e.g., technical drills, interval runs) in male outfield soccer players aged 12–13 years. Both intervention groups exercised for 6 months. The combined training group conducted 4 core strength training and 5 soccer training sessions per week, whereas the soccer training group performed 5 soccer training sessions per week only. Before and after training, subjects were tested for their hip flexors/extensors strength, cross-sectional area of trunk muscles, and athletic performance. With respect to hip strength and physical fitness measures, both intervention groups showed significant but similar performance enhancements in peak torque of the hip flexors (combined training group: $f = 0.45$, isolated training group: $f = 0.74$) and in 15-m sprint test (combined training group: $f = .56$, isolated training group: $f = 0.40$) following training. However, the relative change in peak hip extensor torque was significantly higher in the combined ($f = 1.26$) as compared to the isolated ($f = 0.68$) training group. Furthermore, significant gains in squat (combined training group: $f = 0.33$, soccer training group: $f = 0.06$) and countermovement jump heights (combined training group: $f = 0.62$, soccer training group: $f = 0.12$) were observed in the combined training group only.

Our findings extend the existing results in as much as we additionally observed improvements in measures of flexibility, coordination, and balance following core strength training in youths. With reference to the literature (Allen et al. 2013; Hoshikawa et al. 2013) and our own findings, core strength training appears to be a well-suited conditioning program for the promotion of health-related and skill-related physical fitness in youth. The positive effects of core strength training on physical performance of the lower extremities can most likely be explained by the specific role of the trunk as a linkage between upper and lower extremities. Particularly during every-day or sports-related rotational torso movements, trunk muscles generate torque along a diagonal proximal to distal path to enhance extremity force production. Konin and colleagues (2003) referred to this as the so-called serape (i.e., “shawl-like”) effect. Scientific evidence was provided by Kibler (1995) who was able to show that 51% of total kinetic energy and 54% of total force are developed in the hip and trunk muscles during the tennis serve of professional athletes. According to Young et al. (1996), muscles belonging to the global system (e.g., erector spinae, rectus abdominis, internal/external obliques, latissimus dorsi) primarily generate torque in a serape-like manner during rotational movements (e.g., throwing). Moreover, the trunk acts as a kinetic link that facilitates the transfer of torques and angular momenta between upper and lower extremities during the execution of whole body movements as part of sports and occupational skills, fitness activities, and activities of daily living (Behm et al. 2010). There is evidence for this hypothesis which indicates that during normal human movement, trunk muscle activations (e.g., musculus transversus abdominis) are organized well ahead (110 ms) in anticipation of movement or perturbation to balance in healthy young adults (Hodges and Richardson 1997). Hodges and Richardson (1997) argued that this anticipatory muscle activation helps stiffening the spine to provide a foundation for functional movements. Thus, muscles belonging to the local system (e.g., lumbar multifidus, transversus abdominis) appear to primarily provide proximal stability of the trunk for distal mobility of the limbs. Of note, our core strength training protocols comprising multiple sets with many repetitions or long contraction times may have specifically induced adaptive processes in muscles of the local system (deep muscles) since those muscles are characterized by a relatively high proportion of type I (slow-twitch) fibers (Behm et al. 2010). Interestingly, performance during physical fitness tests significantly improved although postural positions during training and testing conditions were different (i.e., horizontal lying during training vs. upright standing during testing). Despite this difference, transfer effects were notified from core strength exercises performed in vertical directions while lying in horizontal positions to proxies of physical fitness predominately performed in vertical position. Future studies have to elucidate whether core strength training programs conducted in an upright standing position (e.g., Romanian deadlift) may be even more effective in enhancing components of physical fitness in adolescents.

By integrating unstable surfaces in our CSTU exercise protocol, we specifically aimed at activating the deep muscles that are responsible for trunk stability. Nevertheless, our findings indicate that CSTU as compared to CSTS has only limited additional effects (i.e., stand-and-reach test) on physical fitness. In this regard, Willardson et al. (2009) compared trunk muscle activity (i.e., rectus abdominis, external/internal oblique, transversus abdominis, erector spinae) during resistance exercises (i.e., back squat, dead lift, overhead press, curl lifts) performed on stable ground versus the BOSU Balance Trainer in trained young men. The main finding of this study was that no significant differences were found in activity across all examined muscles and lifts when performing the resistance exercises on the BOSU Balance Trainer as compared to stable ground. The authors concluded that the tested resistance exercises can be performed on stable ground without losing the potential trunk muscle training benefits. Our findings of limited additional effects of CSTU as compared to CSTS are in line with the results of this cross-sectional study. To the authors' knowledge, there is no other study available in the literature that compared the effects of CSTS versus CSTU on measures of physical fitness. Therefore, we will discuss a study that investigated the effects of lower extremity strength training using stable versus unstable surfaces on athletic performance in healthy, trained individuals (Cressey et al. 2007). Both intervention groups performed the same exercises (e.g., squats, deadlifts, lunges, single-leg squats) at identical training volumes but on different training surfaces (stable vs. unstable). Following 10 weeks of training, findings were inconsistent in as much as the unstable group showed significantly greater improvements than the stable group in sprint time (stable group: $f = 1.33$, unstable group: $f = 1.50$) and in agility performance (stable group: $f = 0.97$, unstable group: $f = 1.60$). In terms of drop jump power performance, both groups showed similar performance enhancements (stable group: $f = 0.26$, unstable group: $f = 0.11$).

4.4.6 Conclusions

In summary, the results of this study illustrate that core strength training is a feasible (i.e., high adherence rate of ≥81%) and safe (i.e., no injuries reported) training modality that produces marked increases in health (i.e., strength, flexibility) and skill-related (i.e., balance, coordination, speed) components of physical fitness in healthy male and female youths. Contrary to our hypothesis, CSTU as compared to CSTS has only limited additional effects (i.e., stand-and-reach test) on physical fitness. Consequently, if the goal is to enhance physical fitness, CSTU has no advantage over CSTS.

4.4.7 References

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5. General discussion

The main purpose of the thesis was to investigate specific aspects (e.g., acute and long-term effects) of how surface condition affects proxies of athletic performance when implemented in strength training. In fact, little is known about strength training programs under unstable conditions, particularly when incorporating SSC movements, although instability training devices have become popular instruments for young and old, elite athletes and untrained, and for conditioning and rehabilitation. Therefore, cross-sectional studies were conducted in order to analyze biomechanical parameters (i.e., EMG, kinematics, and kinetics) in stable and unstable surface conditions using jump-landing tasks. The latter can be considered essential components of athletic performance in several sports and, in part, everyday activities. Additionally, a longitudinal study contributed to the recent discussion on core strength training that emerged in the scientific community by investigating whether unstable surfaces are superior to stable surfaces in terms of training-induced performance enhancements in youth.

5.1 Effects of surface instability on athletic performance

In general, the findings of this thesis revealed that there is no advantage for instability training devices compared to stable surface conditions regarding enhancement of athletic performance when implemented in different strength training programs (e.g., plyometric training, core strength training) in healthy subjects. Particularly in terms of plyometric training (i.e., an explosive-type strength training method), the results of study 1 and 2 even showed that actual performance during training on unstable surfaces was compromised from an athletic as well as a biomechanical perspective, indicating insufficient and inappropriate training stimuli for long-term performance enhancements. These results support the findings of studies on the effects of strength training programs on stable versus unstable surfaces (Stanforth et al. 1998, Cowley et al. 2007, Cressey et al. 2007, Kibele & Behm 2009, Chulvi-Medrano et al. 2012, Oberacker et al. 2012, Kibele et al. 2014). For instance, Cressey et al. (2007) investigated the effects of 10 weeks of lower extremity strength training using stable versus unstable surfaces on athletic performance in young, healthy soccer players. Following an intervention period (i.e., 2-3 sessions/week), significantly larger gains in jump and sprint performance were reported for the group that trained on stable surfaces compared to the group that trained on unstable surfaces. The authors concluded that the unstable surface used (i.e., inflatable rubber discs) may attenuate performance improvements in healthy, trained athletes. In terms of upper-body strengthening exercises, Cowley et al. (2007) conducted 3 weeks of chest-press training (i.e., 2-3 sessions/week) in previously untrained young women. Subjects performed chest-press exercises either on a flat bench or on a Swiss ball. The authors found that both training programs significantly improved chest-press strength and abdominal power following training without advantages for either group. Similarly, 7 weeks of lower-body plyometric training (i.e., 2 sessions/week) performed on unstable surfaces has been shown to be as effective as that performed on stable surfaces regarding enhancement of athletic performance measures (e.g., drop jump, agility) in physically active but strength training inexperienced subjects (Kibele et al. 2014) Lastly, Stanforth et al. (1998) investigated the effect of a 10-week core strength training program (i.e., 2 sessions/week) conducted either on a Swiss ball or on the floor in physically active, young females. Following the training period, only limited additional effects of the Swiss ball training group compared to the floor training group had been found for the double leg lowering test, whereas changes in all other performance measures (i.e. trunk flexor/extensor strength) were similar in both intervention groups. Summing up these results from the literature and taking into account our own study findings, it appears that implementing unstable surfaces in different strength training programs has no advantage over stable surfaces in terms of enhancing proxies of athletic performance. Furthermore, when conducting strength training on unstable surfaces in trained subjects, performance enhancement may even be inhibited (Cressey et al. 2007, Oberacker et al. 2012).

Interestingly, training studies using balance training only (i.e., without additional load) have generally been very successful at improving not only measures of balance and postural control but also components of athletic performance such as strength, power, and agility (Gruber & Gollhofer 2004, Bruhn et al. 2006, Yaggie & Campbell 2006, Granacher et al. 2010). However, when incorporating demands of balance and strength into the same exercise, one aspect has extensively been discussed that may explain why instability training devices do not provide an extra stimulus for performance gains, particularly in athletes. Namely, Cressey et al. (2007) and Oberacker et al. (2012) argued that lower force and power levels under unstable versus stable conditions may preclude larger gains in muscle strength and thus inhibit enhancements in athletic performance. In fact, whereas untrained individuals respond favorably to most protocols (Kraemer & Ratamess 2004), the adaptive reserve for strength gains appears to be lower in trained subjects compared to novices because of a leveling off with increasing training status (Rhea et al. 2003). Thus, higher training intensities have been recommended for those who are trained (Rhea et al. 2003).

In this regard, it has to be noted that several studies demonstrated impaired levels of force production (Behm et al. 2002, Anderson & Behm 2004, McBride et al. 2006, Saeterbakken & Fimland 2013a, 2013b), power output (Drinkwater et al. 2007, Zemková et al. 2012), and movement velocity (Drinkwater et al. 2007) when performing on instability training devices (e.g., balance pads, BOSU balls, Swiss balls) (Table 12). In accordance with these findings, study 1 revealed significantly lower jump performance as a measure of lower limb power output on balance pads compared to stable floor conditions in young, physically active subjects. For this reason, a recent stand taken by the Canadian Society for Exercise Physiology postulated that, from an athletic perspective, unstable surfaces may be inappropriate when the primary training goal is to gain muscle mass, absolute strength, or muscular power in trained subjects (Behm et al. 2010a). Nevertheless, in terms of youth strength training, the lower level of force and power output on unstable surfaces may still represent a sufficient stimulus for performance enhancement (Behm & Colado-Sanchez 2013). In fact, Faigenbaum and colleagues (1999) previously showed that strengthening programs comprising more repetitions with lower loads significantly improved muscular strength and muscular endurance in children. This may explain why at least similar performance gains were found in physically youth following core strength training using unstable compared to stable surfaces in the longitudinal study of this thesis (i.e., study 4).

Table 12: Sample of force and power output on unstable relative to stable conditions.

Study	**No. of subjects; sex; age (years)**	**Performance output using instability training devices**
Behm et al. (2002)	8; M; 24 ± 7; resistance-trained	Knee extension MIF (Swiss ball): 30 % Plantar flexion MIF (Swiss ball): 80 %
Anderson & Behm (2004)	10; M; 26 ± 6; resistance-trained	Chest press MIF (Swiss ball): 60 %
McBride et al. (2006)	9; M; 25 ± 5; resistance-trained	Squat MIF (balance disc): 54 % Squat IRFD (balance disc): 59 %
Saeterbakken & Fimland (2013a)	16; M; 23 ± 2; resistance-trained	6-RM bench press (balance disc): 93 % 6-RM bench press (Swiss ball): 92 %
Saeterbakken & Fimland (2013b)	15; M; 23 ± 3; resistance-trained	squat MIF (Power board): 93 % squat MIF (BOSU ball): 81 % squat MIF (balance cone): 76 %
Drinkwater et al. (2007)	14; M; 23 ± 4; physically active	Squat concentric force (balance pad): 82% Squat concentric power (balance pad): 76%
Zemková et al. (2012)	15; M; 23 ± 3; resistance-trained	Squat concentric power (BOSU ball): 83 % Chest press concentric power (Swiss ball): 93 %
study 1	*29; F, M; 23 ± 3; physically active*	*Drop jump height (balance pad): 91 %*

F = females, IRFD = isometric rate of force development, M = males, MIF = maximal isometric force, RM = repetition maximimum

Of note, coaches and practitioners are interested not only in efficacy but also in the safety of their training programs. Regarding plyometric exercises, the findings of the thesis (i.e., study 2) indicate that instability training devices appear to pose a greater challenge to maintaining neuromuscular control and biomechanical integrity of the knee. More precisely, acute adaptations in frontal (i.e., larger knee abduction [valgus]) and sagittal plane kinematics (i.e., insufficient knee flexion) during jumping and landing from a jump on unstable surfaces may be associated with an increased risk of sustaining non-contact ACL injury, particularly in females. In previous literature, these biomechanical characteristics were emphasized as two important risk factors that most likely contribute to ACL injury during jump-landing tasks (Derrick 2004, Olsen et al. 2004, Chappell et al. 2007, Krosshaug et al. 2007, Myer et al. 2012). Further, in a review article, Orchard (2002) discussed the role of surface condition (e.g., compliance) for (lower limb) injury risk in different team sports. The findings were inconsistent due to confounding variables, such as shoe-surface traction or the size of the playing field (Orchard 2002). However, considering the present results and the findings of previous studies investigating surface effects on SSC kinematics (Ferris & Farley 1997, Ferris et al. 1998, Kerdok et al. 2002, Moritz & Farley 2003, Derrick 2004), stable surface conditions appear to be more safe than unstable/foam surfaces during plyometric exercises. Further, instability-induced decrements in kinematic parameters such as knee flexion were found in slow-velocity movements (i.e., dynamic squats) as well (Drinkwater et al. 2007). Given these detrimental effects in terms of exercise technique, it can be argued that coaches should use instability training devices and additional loads carefully with respect to the intended training goal.

5.2 Neuromuscular adaptations to surface instability

From a mechanistic point of view, study 1 of this thesis indicates that lower performance output during jump-landing tasks on unstable compared to stable surfaces may be attributed to lower levels of EMG activity of the leg muscles. In particular, it was concluded that modified feedforward activation mechanisms in leg muscles during the preactivation phase and/or possible alterations in leg muscle activity shortly after ground contact are responsible for performance decrements. In fact, leg muscle activation levels of time intervals that have been found with lower muscle activity on unstable surfaces in study 1 (i.e., 100 ms prior to ground contact, 30-60 ms after the instant of touch-down) were discussed as affecting muscle stiffness of the main kinetors and, thus, are import for SSC performance output (Gollhofer et al. 1984, Avela et al. 1996, Horita et al. 1996, Komi & Gollhofer 1997, Nicol & Komi 1998).

The results of the thesis are in line with several studies that reported lower limb muscle activity during strengthening exercises (e.g., squats, push-ups) under unstable compared to stable conditions (McBride et al. 2006, McBride et al. 2010, Saeterbakken & Fimland 2013a, 2013b). However, it has to be noted that there is a controversy in the literature regarding this issue (Behm et al. 2002, Anderson & Behm 2004, Anderson & Behm 2005). It may be that specific methodological reasons (i.e., absolute vs. relative loads) account for the observed discrepancy in the literature. For instance, Anderson and Behm (2005) applied the same absolute weight for stable and unstable test conditions and found higher leg muscle

EMG in m. soleus when performing dynamic squats on balance discs compared to the floor. Given that maximal force output is impaired on unstable conditions, using similar absolute loads on stable and unstable surfaces corresponds to higher relative loads (e.g., in percent of the one repetition maximum) under unstable conditions and may thus be responsible for the higher muscle activity observed with instability. Indeed, reduced leg muscle activity was reported during dynamic squats on unstable compared to stable surfaces when the same relative load was used (McBride et al. 2010).

In terms of core strength training investigated in study 4, exercises were performed with similar absolute intensity (i.e., body mass) on stable and unstable surfaces. In support of the aforementioned consideration of loading condition and muscle activation, previous studies reported higher trunk muscle activity when similar absolute loads were used on stable and unstable surfaces (Vera-Garcia et al. 2000, Imai et al. 2010, Snarr & Esco 2014). Thus, it was stated that instability training devices may serve as a means to increase stimuli during core strength training programs (Snarr & Esco 2014). However, only limited additional effects on physical fitness (i.e., stand-and-reach test) were observed for core strength training on unstable surfaces in study 4. It can be speculated that, in spite of potentially higher trunk muscle activation on unstable surfaces, altered demands on the motor control system (e.g., muscle coactivation) are responsible for these findings. For instance, the ratio of antagonist-agonist activity was about 40 % higher during unilateral knee extensions on a Swiss ball compared to the same muscle action on a bench (Behm et al. 2002). Similarly, during ground contact of drop jumps on unstable surfaces, 11-25 % lower activation levels of agonistic muscles (i.e., m. vastus medialis, m. gastrocnemius) were observed compared to stable surfaces in study 1 of this thesis. In contrast, antagonistic muscles (i.e., m. biceps femoris, m. tibialis anterior) revealed no differences in activation levels between surface conditions. Regarding core strengthening exercises, Vera-Garcia et al. (2000) also concluded that muscle activity level and the method of muscular co-activation change when performing crunches on unstable surfaces. Although increased co-activation may support joint stabilization, it seems reasonable to assume that such activation patterns can hamper the force and power output of agonistic muscles (Cressey et al. 2007, Behm et al. 2010b). Torque developed by the antagonists decreases net torque in the desired direction and may impair an individual's ability to completely activate the agonists through reciprocal inhibition (Sale 2003). Sale (2003) described two methods of adaptation in muscular activation patterns with continuous strength training: 1) a decrease in absolute antagonist activity together with either an increase or no change in agonist activity, or 2) no change in absolute antagonist activity but increased agonist activity. Both ways of adapting will decrease the ratio of antagonist-agonist activity and increase net torque production in the desired direction. Muscular activation patterns during (core) strength training on unstable surfaces may be contrary to both of these processes. Consequently, it can be speculated that inappropriate adaptations in neuromuscular activation patterns following core strength training on unstable surfaces are responsible for the finding that using instability training devices is not superior to using stable ground during training.

Lastly, the present findings of study 1 and study 2 also indicate modified neuromuscular control of the knee in the frontal plane during jump-landing tasks under unstable compared to stable conditions. More specifically, a balanced medial-to-lateral muscle activation at the knee joint is necessary to prevent individuals from excessive frontal plane motion in the knee (Myer et al. 2005, Hewett et al. 2006). For instance, Myer et al. (2005) reported a lower ratio of medial to lateral quadriceps muscle activation in females compared to males and suggested that this neuromuscular control strategy may contribute to dynamic valgus motion of the knee in females. Additionally, Hewett et al. (2006) argued that unbalanced medial-to-lateral quadriceps activation together with unbalanced medial-to-lateral hamstring activation may be related to lower knee joint control in the frontal plane. Further, the authors stated that this modified control strategy of the knee joint is associated with an increased risk of sustaining non-contact ACL injury during high-risk maneuvers, such as jump-landing tasks. Accordingly, the results of this thesis (study 1 and study 2) showed lower activity in medial knee joint muscles (i.e., m. vastus medialis), similar activity in lateral knee joint muscles (i.e., m. biceps femoris), and higher knee valgus angles during drop jumps on unstable compared to stable surfaces. With respect to the statements of Myer et al. (2005) and Hewett et al. (2006), it seems reasonable to assume that changes in neuromuscular control of the knee contributed to higher knee valgus and finally to an increased risk of ACL injury during jump-landing tasks involving instability.

5.3 The role of the core on stable and unstable surfaces

When performing strengthening exercises on unstable surfaces, trunk muscles have been proposed to play a specific role to ensure postural stability. In fact, these muscles were discussed as a part of a muscular box called the “core” that provides proximal stability for distal mobility during sports skills, fitness activities, and even activities of daily living (Kibler et al. 2006, Akuthota et al. 2008, Behm et al. 2010b). Notably, whereas force and power output is lower during lower and upper limb exercises on unstable surfaces, studies demonstrated that the activity of trunk muscles is similar (Anderson & Behm 2004, McBride et al. 2010, Saeterbakken & Fimland 2013b) or even higher (Anderson & Behm 2005, Marshall & Murphy 2006, Bressel et al. 2009, Sundstrup et al. 2012, Saeterbakken & Fimland 2013a) compared to exercises on stable surfaces. Given that, Behm and Anderson (2006) suggested that at least similar extents of muscle activation accompanied by decreased force/power output with instability indicate that the motive forces of the muscles (i.e., the muscles’ ability to apply external force) were transferred into greater stabilizing forces. In other words, although externally-measured forces are impaired by unstable surface conditions, muscle activation will be maintained or even increased because of the increased demand on stabilization (Behm and Anderson 2006). In accordance with previous findings (Anderson & Behm 2004, McBride et al. 2010, Saeterbakken & Fimland 2013b), study 1 of the thesis revealed no differences in trunk muscle activity, whereas performance output (i.e., jump height) was lower during jump-landing tasks on unstable compared to stable surfaces. Considering the statement of Behm and Anderson (2006), it can be argued that the level of trunk muscle activity during drop jumps and landings on unstable surfaces was maintained in order to resist perturbations of postural stability during performance.

On the other hand, the findings of similar activation levels of the trunk muscles during jump-landing tasks under stable and unstable conditions may also indicate that the trunk only plays a minor role in athletic performance in general and performance on unstable surfaces in particular. In this regard and with reference to the classification suggested by Vincent and Weir (2012), significant but only small associations between behavioral (i.e., trunk muscle strength, jump performance, lower limb kinematics) and neuromuscular data (i.e., trunk and leg muscle activity) were found irrespective of surface condition during drop jumps in study 3. Similarly, previous investigations reported significant but small associations ($r \leq 0.62$) between measures of trunk muscle strength (e.g., isometric trunk muscle endurance) and athletic performance (Table 13).

Table 13: Sample of associations between measures of trunk muscle strength (TMS) and athletic performance.

Study	**No. of subjects; sex; age (years)**	**Trunk muscle strength (TMS)**	**Strength/ power/ agility/ performance test**	**size of correlation**
Nesser et al. (2008)	29; M; 18-23; NCAA Division I football players	Trunk extension/ flexion endurance; lateral trunk muscle endurance	Bench press, squat and power clean 1-RM; 20-yd and 40-yd sprint; shuttle run; CMJ	TMS vs. 1RM: small association, $r^2 < 39$ %; TMS vs. sprint: small association, $r^2 \leq 36$ %; TMS vs. agility: small association, $r^2 \leq 30$ %; TMS vs. power: small association, $r^2 \leq 35$ %
Wells et al. (2009)	24; F, M; 23 ± 5; National Golf Team members	Trunk flexion endurance; lateral trunk muscle endurance	Golf ball speed; golf ball carry distance; golf performance statistics (e.g., mean score)	TMS vs. golf performance: small association, $r^2 < 35$ %
McKean & Burkett (2010)	29; F, M; 25 ± 5; national kayakers	Double leg lowering	Bench press and pull up 1-RM; bench pull test; kayak race performance (i.e., 500 m, 1000 m)	TMS vs. strength: small association, $r^2 < 8$ %; TMS vs. power: small association, $r^2 \leq 16$ %; TMS vs. kayak performance: small association, $r^2 \leq 30$ %
Okada et al. (2011)	28; F, M; 24 ± 4; recreational athletes	Trunk extension/ flexion endurance; lateral trunk muscle endurance	Backward overhead medicine ball throw; T-run agility test; repetitions in single-leg squat	TMS vs. power: small association, $r^2 < 3$ %; TMS vs. agility: small association, $r^2 \leq 20$ %; TMS vs. leg muscle endurance: small association, $r^2 \leq 25$ %
study 3	*29; F, M; 23 ± 3; physically active students*	*Maximal isokinetic strength of trunk flexors/extensors*	*Drop jump (stable/ unstable surface)*	*TMS vs. power: small association,* $r^2 < 44$ *%*

CMJ = countermovement jump, F = females, M = males, RM = repetition maximum, TMS = trunk muscle strength

Further, the study of Keogh et al. (2010) examined the impact of surface condition on associations between isometric trunk muscle endurance and maximal upper extremity strength (i.e., seated shoulder dumbbell press). The authors only observed a significant but small correlation ($r = 0.48$) between muscle endurance of trunk flexors and the dumbbell press performed on a Swiss ball relative to a bench. In accordance with the literature, study 3 of this thesis found significant but small associations ($0.50 \leq r \leq 0.66$) between muscle strength of trunk extensors and drop jump performance, irrespective of surface condition. Of note, the present thesis extends the findings of the aforementioned studies by conducting maximal dynamic (isokinetic) instead of submaximal isometric trunk muscle testing. Submaximal isometric muscle actions may not be adequate to illustrate the importance of trunk muscle strength for athletic performance, because many sports-related movements (e.g., jumping) require maximal and explosive force/torque production. Additionally, these findings were reinforced on a neuromuscular level by small correlations ($0.45 \leq r \leq 0.68$) between trunk and leg muscle activity, irrespective of surface condition.

However, although cause-and-effect relations are not conclusively allowed, the results of these cross-sectional studies and of study 3 of this thesis imply that measures of trunk muscle strength and athletic performance are independent of each other and may thus have to be trained in a complementary manner. In fact, study 4 revealed increases in 3 of the 6 investigated athletic performance measures (i.e., coordination, dynamic balance, flexibility) following CSTS and/or CSTU in youth. On the contrary, measures such as jump performance assessed by the standing long jump appeared to be unaffected by either core training program. Accordingly, whereas 12 weeks of CSTS (i.e., 3 sessions/week) improved dynamic balance in healthy adolescent soccer players (Imai et al. 2014), Sharma et al. (2012) found that there were no differences in spike jump, countermovement jump, and squat jump performance following 9 weeks of combined CSTS and volleyball training (i.e., 5 sessions/week) compared to volleyball training only in university- and state-level volleyball players. Additionally, Tse et al. (2005) reported significant group × test interactions for isometric trunk muscle endurance in favor of combined CSTS and rowing training (i.e., 2 sessions/week) compared to rowing training only in young adult rowers. However, no changes were found in any of the proxies for athletic performance (e.g., CMJ height, 10-m shuttle run time, 40-m sprint time) following 8 weeks of combined training. Thus, it can be argued that, depending on training modalities (e.g., training duration and frequency) and/or other factors (e.g., age, prior experience), CSTS/CSTU has selected beneficial effects on athletic performance primarily on the level of coordination and postural control, rather than maximal force and power output.

6. Practical relevance

The studies conducted in the present thesis were designed to investigate the role of surface condition in athletic performance using a relatively wide research approach. Therefore, methods comprised an assessment of behavioral (i.e., performance) as well as mechanistic (i.e., neuromuscular) data. Finally, the results revealed the acute and long-term adaptations and underlying mechanisms occurring during popular strength training regimens (i.e., plyometric training, core strength training) implementing unstable surfaces. Given that instability training devices are frequently used in a variety of training settings (e.g., athletic training, physical fitness, rehabilitation), the findings of this thesis provide important insights for many coaches, practitioners, and athletes as to whether and how to incorporate unstable surfaces in strength training programs with respect to the individual’s initial training status and the intended training goal.

Generally, it can be stated that implementing unstable surfaces in strength training programs has no advantage over stable surfaces in terms of enhancing proxies of athletic performance. Further, it appears that exercises with higher-level force and power output are even more suitable on firm and stable ground to stimulate the desired adaptations for enhancements of strength, power, or movement velocity. In fact, when implementing unstable surfaces during strengthening exercises (e.g., squats, chest press, crunches, or even jumps), strength and power output is impaired, indicating lower training stimuli of unstable devices. Of note, progression of training requires higher loads in trained compared to untrained individuals in order to induce the desired adaptations (Rhea et al. 2003). Consequently, instability training devices such as balance pads, wobble boards, or Swiss balls should be used with caution during strength training, particularly in athletes. Otherwise, adaptions can be attenuated by unstable conditions in experienced individuals who train for maximal strength or power.

In the untrained however, the lower force/power output during strength training under unstable conditions appears to be still effective for gains in muscle strength and thus for the enhancement of athletic performance. Namely, changes in proxies of athletic performance following strength training programs in youth appear to be unaffected by the surface conditions used during the training program. Thus, regarding fitness- and health-conscious individuals with less experience in systematic strength training (e.g., youth, recreationally active persons), unstable devices and/or surfaces can be expected to be appropriate instruments for stimulus variety during strength training. In other words, the present thesis suggests that "traditional" strength training sessions under stable conditions can easily be conducted in combination with training sessions using instability training devices to provide a greater variety of training experiences without attenuating training benefits in untrained individuals.

Further, the concept of training variation, also referred to as periodization, describes the need to continuously modulate volumes, movement velocities, or intensities of training over different time periods to maximize the outcomes. The training program used has to be systematically altered in order to optimize both performance and recovery in individuals with diverse backgrounds and fitness levels (e.g., athletes, advanced, novices) (Kraemer & Ratamess 2004). Taking this into account, coaches and practitioners could implement unstable surfaces in strength training as an alternative to stable conditions in untrained individuals as well as in athletes, especially during phases when exercises have to be performed at lower training intensity (Behm et al. 2010a). Additionally, unstable surfaces can also be considered an important assistance for individuals recovering from injury (Behm & Colado 2012). For these patients, lower intensities are indicated. One can argue that unstable surfaces may be an appropriate tool for training progression without substantially increasing training load.

Nevertheless, when implementing instability training devices in strength training, it has to be noted that neuromuscular activation patterns may be altered as compared to stable conditions. The changes in neuromuscular activation patterns during exercises on unstable surfaces may be responsible for lower maximal performance output, but also for a greater risk of sustaining non-contact injury (e.g., of the knee). Regarding the latter, this may be particularly relevant during movement tasks with explosive force production and relatively high movement velocities, such as jump-landing tasks. Thus, before implementing balance pads, etc. in strength training programs to enhance athletic performance, coaches and therapists should be aware of the individual's training status and training goal, training period and type of exercise (i.e., isometric, slow-velocity dynamic, explosive dynamic), and pay attention to the level of instability used.

Lastly, regarding practical implication and recommendations, the present thesis further indicates that the frequently claimed importance of trunk muscles for athletic performance, particularly with instability, has been overestimated. Generally, core strength training appears to be a feasible and safe training modality in untrained individuals (i.e., male and female youth). However, there are only small associations between measures of trunk muscle strength and athletic performance irrespective of surface condition. In fact, increasing trunk muscle strength appears to have selected beneficial effects on athletic performance primarily on the level of coordination and postural control, rather than maximal force and power output. Additionally, strengthening trunk muscles on unstable surfaces is not superior to stable surfaces in terms of performance enhancements. Accordingly, instability during athletic performance does not require higher levels of trunk muscle strength in order to resist potential perturbations of postural stability. Thus, it can be concluded that in order to enhance performance on unstable surfaces, exercises that are more task-specific should be used. For instance, referring to the exercises of the present thesis, it would be more efficient to increase leg muscle strength instead of trunk muscle strength in order to enhance jump performance on the floor or on a balance pad.

7. Limitations and perspectives

In the present thesis, 3 cross-sectional studies and 1 longitudinal study were conducted to investigate the role of surface condition in athletic performance. Based on the cross-sectional studies, acute effects on performance output and biomechanics during jump-landing tasks on unstable compared to stable surfaces could be identified. It has to be noted, though, that only one instability training device (i.e., Airex© Balance Pad) has been used. Previously, it was shown that the level of instability does affect neuromuscular performance (Wahl & Behm 2008, Saeterbakken & Fimland 2013a, 2013b). Thus, it seems reasonable to question how performance and, in particular, biomechanical behavior depend on the level of instability during jump-landing tasks.

More importantly, in order to substantiate the results of the present cross-sectional studies, future studies should focus on longitudinal approaches. In terms of plyometric training, Kibele et al. (2014) recently reported similar performance enhancements following a 7-week lower body training program on stable and unstable surfaces. Unfortunately, from a mechanistic point of view, they did not assess EMG or kinematic parameters. It remains unclear whether neuromuscular and/or biomechanical adaptations occurred under either condition. Therefore, it can be concluded that more longitudinal studies are needed to analyze the potential changes in muscle activation patterns and kinematic movement characteristics as a result of instability in plyometric training (Kibele et al. 2014).

Moreover, in reference to the cross-sectional studies of this thesis, it would be scientifically interesting to include unstable testing conditions in future longitudinal research attempts as well. Notably, while instability training devices have been used during training in our own study on core strength training and in the study on plyometric training (Kibele et al. 2014), all tests were performed under stable surface conditions only (i.e., regular gym floor). Including stable and unstable surfaces in the testing procedure could provide more insight into the generality and specificity of performance enhancements with respect to the surface condition used during training. In other words, it is unclear yet to what extent performance gains in stable conditions following strength training on stable surfaces can be transferred to performance in unstable test conditions, and/or to what extent performance gains in unstable conditions following strength training on unstable surfaces can be transferred to performance under stable conditions.

In addition to methodological limitations, the study of Kibele et al. (2014) as well as the longitudinal study of this thesis reveal one conceptual restriction: subjects were randomly assigned to one of two experimental groups, but no control group was included. In a randomized controlled trial, the effects of the intervention are always related to a comparator (Zwarenstein et al. 2008). Of course, comparisons of plyometric training/core strength training on unstable versus stable surfaces can be used to determine the efficiency of training under unstable conditions. However, in order to determine the efficacy of strength training programs using unstable surfaces, groups receiving experimental treatment have to be compared to control groups receiving no treatment. By doing so, one can ultimately identify whether performance changed due to training or due to a systematic bias. Thus, future studies investigating strength training programs under unstable conditions should (also) include passive control groups.

One last aspect of this thesis which needs to be considered is that subjects' characteristics were not consistent throughout all included studies. Indeed, physically active young men and women who were experienced in plyometrics participated in the cross-sectional studies (study 1 to 3), whereas physically active adolescent boys and girls inexperienced in systematic strength and balance training were recruited for the longitudinal study (study 4). Given that age (Lemmer et al. 2000) and training status (Ahtiainen et al. 2003) can have an effect on adaptations to strength training, the transfer of each of the present findings from one subject group to another is limited. More research on strength training programs using unstable surfaces is needed, taking into account different subject preconditions (e.g., age, sex, training status).

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Authors' contribution

The present thesis is designed as a cumulative dissertation. In this regard, four scientific articles have been prepared, submitted to peer-reviewed journals, and accepted for publication. According to the local doctoral degree regulations (§ 7 (4), sentence No. 2), significant contributions to the articles from the respective co-authors were acknowledged and finally confirmed by each co-author:

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Study	Design	Data collection	Data analyses	Interpretation	Manuscript
Chap. 4.1	**OP**, TM, AK, DB, UG	**OP**, TK	**OP**, TM, UG	**OP**, TM, SM, UG	**OP**, TM, SM, AK, DB, UG
Chap. 4.2	**OP**, TM, AK, DB, UG	**OP**, TK	**OP**, TM, UG	**OP**, TM, UG	**OP**, TM, AK, DB, UG
Chap. 4.3	**OP**, TM, AK, DB, UG	**OP**, TK	**OP**, TM, UG	**OP**, TM, UG	**OP**, TM, AK, DB, UG
Chap. 4.4	**UG**, JPB, TM	JS, KK	**UG**, JS, KK, TM	**UG**, JS, KK, OP, TM	**UG**, JS, KK, OP, JPB, TM

Note: First author is highlighted in bold