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Core stability in soccer

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Core Stability in Soccer: it's a Matter of Control!

Measuring and Training Stability in Elite Youth Soccer

Arend Jan Borghuis

Core Stability in Soccer: it's a Matter of Control!

Measuring and Training Stability in Elite Youth Soccer

Stellingen

Behorende bij het proefschrift
Core Stability in Soccer: it's a Matter of Control!
Jan Borghuis, 13 november 2013

1. Het maken van onderscheid tussen de concepten 'core stability' en 'spine stability' is essentieel in discussies aangaande het effect van een goede rompstabiliteit op prestaties en blessures (*dit proefschrift*).
2. Meer aandacht voor lichaamsbeheersing in de vorm van neuromusculaire training verbetert de balans en wendbaarheid bij voetballers (*dit proefschrift*).
3. Hoewel veel jeugdige voetballende toptalenten menigmaal vast in hun schoenen staan, valt er op stabiliteitsniveau vaak nog veel winst te boeken (*dit proefschrift*).
4. Wie niet sterk is, moet stabiel zijn (*dit proefschrift*).
5. Het belang van stabiliteit om de top te kunnen halen, staat zo vast als een huis. Eenmaal de top bereikt, kunnen de pannen van het dak worden gespeeld.
6. Stabiliteit vormt de basis om te kunnen promoveren.
7. Core stability is core business.
8. Balance recognizes that many good things in life are good only in moderation.
9. 'Sport is de belangrijkste bijzaak in het leven' (*Kees Jansma*).
10. De laatste loodjes...

All research presented in this thesis has been conducted at:

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Arend Jan Borghuis
geboren op 12 september 1985
te Kampen

Promotores:	Prof. dr. K.A.P.M. Lemmink Prof. dr. C. Visscher
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1. General Introduction

Background

The concept of core stability has gained a lot of attention in the worlds of sport and rehabilitation. It has become a buzz word in the current sports and fitness industry and core stability training is immense popular. As a consequence of this, core stability has become a catch-all term. Even approaches from very old training methods like Pilates or yoga are nowadays being labelled as core stability training. Searching on the internet and looking in the scientific literature on medicine and sports, various visions can be found regarding core stability training. Some of them focus on contracting the deep laying core muscles, while others integrate core training in exercises in which whole-body movements are performed.

Core stability has been proposed as an important concept in clinical rehabilitation and in the training of competitive athletes. Coaches in various sport disciplines integrate core stability training into their regular training programs. Claims are often put forward that improving core stability will lead to better posture and balance, that it will lead to improvements on speed and agility and that is will lower the risk of sustaining an injury. At the same time, core stability remains a rather vague concept about which a lot of discussion is going on. What actually is the effect of having a stable core on improving performance and preventing injuries? And which training methods are most suitable to train the core?

The fact that there is so much obscurity about the concept, is mainly due to the lack of a clear theoretical framework. Various disciplines have created their own view on core stability. Physiotherapists mainly work from a pathological approach with a focus on neuromuscular control and endurance of the core muscles. On the other hand, physical coaches working with competitive athletes strive after optimizing performance, thereby focusing more on endurance, strength and power. The focus varies per sport discipline and even within a certain sport.

Theoretical Framework

The lack of clarity present in the scientific literature and in the field of practice is not so much because of vagueness about the definition of the core. The core of the human body is often seen as the base from which all movements occur. For the purpose of the present thesis, the core is defined as the lumbar vertebral column with all its surrounding tissues, both passive (tendons and ligaments) and active (muscles). It is often claimed that a stable core is important to optimize the transfer of forces from one body part to another, through which we move ourselves or objects. But what is meant by a *stable* core? That is, what exactly is the definition of stability? This is where problems show up.

Therefore, the starting point for the present thesis is a clear definition of the term stability. For the purpose of the present thesis, stability is considered identical to balance: the ability to maintain or resume a vertical body position. Taking into account the velocity of the body's center of mass (CoM) in dynamic situations, Hof et al.[5] have shown that stability can be achieved by requiring that the so-called 'extrapolated CoM position' should be within the body's base of support. In this way, maintaining stability is all about postural control. Soccer is a good example of an activity in which this ability is heavily challenged. A player makes sharp turns in full run, is perturbed by bodily contact with other players, and at critical moments has to use one leg for playing the ball (figure 1). The term 'stability' is usual in this respect, but it should thus not suggest something stable or static. 'Core stability' is then defined as the part played by the 'core' or lower trunk in this stability process: the ability of the neuromusculoskeletal system to control trunk position in labile situations or in response to sudden balance perturbations.

Figure 1. Typical soccer action in which stability is challenged.

It should be kept in mind that a fully different concept of core stability can also be found in the literature. This concept relates to the structural stiffness of the vertebral column.[8] To know which concept of core stability is used, one is often obliged to investigate the tests that are used. In this respect, the construct validity of many existing measurement methods may be questioned. Existing tests that pretend to measure core stability mainly focus on static core muscle endurance.[3,7,10] Some of these tests consist of observing and classifying the performance on static exercises to judge the control over the deeper core muscles.[6,17] This problem is also found in studies investigating the relationship between core stability and performance. Several studies used McGill's 'core stability' tests to find a relationship between an improved core stability and improvements in functional movement, strength and power.[11,12,15,16] However, McGill's tests were initially developed to measure isometric core endurance in patients with low back problems.[9] The name 'core stability test' for this test is thus quite inappropriate. An improvement on a core endurance test does not have to mean that strength or power have improved in a functional task. It is important to measure the intended result of a training. In this respect, the lack of clarity in the existing scientific literature is to a large extent created because the terms core stability, core strength and core endurance are used interchangeably. The present thesis is an attempt to give more insight on the scientific rationale behind the concept of core stability.

Purpose of the Thesis

The first aim of the present thesis is to have a closer look at the concept of core stability from a scientific perspective. This thesis attempts to provide a universally usable definition of core stability, to stimulate that future discussions regarding the subject matter concern one and the same concept. The second aim is to present valid and reliable measurement methods to quantify core stability, based on the definition formulated. The third aim is to study the effect of a soccer specific neuromuscular training program (NMTP) on core stability in elite youth soccer players, using these measurement tools. Besides, as a secondary aim, the effect of the training program on standing balance and agility as performance measures and on injury occurrence is investigated.

Outline of the Thesis

Chapter 2 further dwells on the concept of core stability. The core of the human body is demarcated and the term stability is defined from a biomechanical perspective. The importance of strength, endurance and sensory-motor control are discussed. This chapter also shows that there actually is not much known about the relationship between core stability and sports performance, mainly due to a lack of unambiguous measurement and training methods. Regarding the relationship between core stability and injury, several studies have shown that decreased proprioception and delayed reflex responses of the core muscles are a risk factor for low back pain and lower extremity (mainly knee) injury.[1,4,13,14,18,19] Chapter 2 ends with considerations regarding core training and descriptions of existing methods aimed at evaluating core stability.

Based on the definition formulated and the already available methods described in chapter 2, a new measurement method is developed as described in chapter 3. On the basis of a study by Radebold et al.,[14] core muscle response times and postural reactions are measured during a sitting balance task in which the balance of the subjects is unexpectedly perturbed. The study is conducted with high-level amateur soccer players and less active nonplayers. The outcome measures of the sitting balance task mainly indicate the speed of reactions in response to a sudden perturbation. Next to the aspect of speed, it is also important to have an indication of the accuracy of the responses. Furthermore, as the definition of core stability shows, stability is not only about reflexive control in response to sudden external perturbations, but stability of the core is also challenged by internal perturbations of the human body itself during labile situations.

Taking these notions into account, together with some practical criteria, new measurement methods are developed to quantify core stability. Chapter 4 describes these methods: the graduated sitting balance test and the seated perturbation test. The principle behind the graduated sitting balance test is based on the narrow ridge balance test developed by Curtze et al.[2] This test actually provides a level of core stability. In the seated perturbation test, performance is measured during a task in which stability is challenged by external perturbations. The outcome measure of the test encompasses a combination of both speed and accuracy of the responses. In chapter 4 the reliability of both tests is investigated, together with an adapted version of the narrow ridge balance test, in a group of 30 students. This study also describes relationships between the different test results.

In chapter 5, the measurement methods to quantify core and whole-body stability are used to determine the effect of a soccer specific neuromuscular intervention program on stability in 90 elite youth soccer players who are followed during one soccer season. Besides stability, also agility is measured and data on injury occurrence are collected.

The thesis ends with a general discussion in which the main outcomes are summarized and discussed. Theoretical and practical implications are put forward and limitations of the present research are described, together with recommendations for future work to be done.

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2. The Importance of Sensory-Motor Control in Providing Core Stability: *Implications for Measurement and Training*

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Contents

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Abstract

Although the hip musculature is found to be very important in connecting the core to the lower extremities and in transferring forces from and to the core, it is proposed to leave the hip musculature out of consideration when talking about the concept of core stability. A low level of co-contraction of the trunk muscles is important for core stability. It provides a level of stiffness, which gives sufficient stability against minor perturbations. Next to this stiffness, direction-specific muscle reflex responses are also important in providing core stability, particularly when encountering sudden perturbations.

It appears that most trunk muscles, both the local and global stabilization system, must work coherently to achieve core stability. The contributions of the various trunk muscles depend on the task being performed. In the search for a precise balance between the amount of stability and mobility, the role of sensory-motor control is much more important than the role of strength or endurance of the trunk muscles. The CNS creates a stable foundation for movement of the extremities through co-contraction of particular muscles. Appropriate muscle recruitment and timing is extremely important in providing core stability.

No clear evidence has been found for a positive relationship between core stability and physical performance and more research in this area is needed. On the other hand, with respect to the relationship between core stability and injury, several studies have found an association between a decreased stability and a higher risk of sustaining a low back or knee injury. Subjects with such injuries have been shown to demonstrate impaired

postural control, delayed muscle reflex responses following sudden trunk unloading and abnormal trunk muscle recruitment patterns. In addition, various relationships have been demonstrated between core stability, balance performance and activation characteristics of the trunk muscles. Most importantly, a significant correlation was found between poor balance performance in a sitting balance task and delayed firing of the trunk muscles during sudden perturbation. It was suggested that both phenomena are caused by proprioceptive deficits.

The importance of sensory-motor control has implications for the development of measurement and training protocols. It has been shown that challenging propriocepsis during training activities, for example, by making use of unstable surfaces, leads to increased demands on trunk muscles, thereby improving core stability and balance. Various tests to directly or indirectly measure neuromuscular control and coordination have been developed and are discussed in the present article. Sitting balance performance and trunk muscle response times may be good indicators of core stability. In light of this, it would be interesting to quantify core stability using a sitting balance task, for example by making use of accelerometry. Further research is required to develop training programmes and evaluation methods that are suitable for various target groups.

Core stability is a hot issue in today's medical world, especially in sport rehabilitation, but at the same time, it is still quite a vague concept about which there is much discussion. Questions are taken into consideration as to whether core stability is important with respect to injury prevention of the back and the lower extremities and what effect core stability has on power and endurance during athletic performance. However, when talking about the concept of core stability, it is relevant to first have a common general definition, thereby assuring that the discussion surrounds one and the same concept.

The purpose of the present article is to give an overview of the existing literature with respect to several issues related to core stability. There are various notions about the composition and functioning of the core. Several attempts to define core stability have been found in the literature. This article looks at the importance of core strength within the concept of core stability. An overview is given of the relevant body structures and tissues that are important in providing core stability with special attention to the muscular system. Furthermore the role of strength, endurance and sensory-motor control is reviewed.

In the second part of this article, literature findings will be discussed regarding the relationship between core stability on the one hand and athletic performance and injury on the other hand. The role of deficiencies in sensory-motor control with respect to clinical instability and lower extremity and low back injuries will be discussed in further detail.

In the existing literature, core stability is often associated with the maintenance of balance, especially in measurement and training procedures. To clarify this relationship, an overview is given about the association between core stability, balance performance and the results of various studies in which electromyographic (EMG) measurements of the trunk muscles have been made during perturbation tasks. First, some studies are discussed in which muscle reaction times and muscle recruitment patterns have been investigated in patients with low back pain. Subsequently, the relationship between core stability and balance is taken into consideration and eventually an overview is presented about the correlations found between balance performance and EMG-measurement results.

Section 4 of this review is mainly dedicated to the role of coordinative and proprioceptive training in enhancing core stability. Special focus is given to the effects of exercises in which a Swiss ball is used as a training aid.

Finally, we look at the current ways in which core stability is being measured. First, some issues are discussed with respect to the measurement of trunk muscle strength and endurance. Eventually, several tests will be considered that have been used to directly or indirectly measure neuromuscular control and coordination.

PubMed was used to search for articles. Search terms included 'core stability', 'trunk stability', 'lumbar spine stability', 'core strength' and 'neuromuscular core control' and these were combined with terms such as 'measurement' or 'training'. Various review articles were found containing useful references. The present article is based on a selection of the most valuable and relevant of these articles.

1. About Core Stability

The term 'core stability' has received a lot of attention, especially in the past few years. It is stated that core stability is a key component in the training programmes of individuals who are aiming to improve their health and physical fitness, but core stability is also an important concept in clinical rehabilitation and in the training of competitive athletes.[1]

1.1 The Core

Particular attention has been paid to the core because it serves as the centre of the functional kinetic chain. The core is seen as a muscular corset that works as a unit to stabilize the body and in particular the spine, both with and without limb movement.[2] In the alternative medicine world, the core has been referred to as the 'powerhouse', the foundation or engine of all limb movement.[2] Kibler et al.[3] also stressed the importance of the core in providing local strength and balance, in decreasing back injury and in maximizing force control.

The core of the body includes both passive and active structures: the passive structures of the thoracolumbar spine and pelvis and the active contributions of the trunk musculature.[4] Akuthota and Nadler[2] described the core as a box with the abdominals in the front, the paraspinals and gluteals in the back, the diaphragm as the roof and the pelvic floor and hip girdle musculature as the bottom. Kibler et al.[3] state that the musculoskeletal core of the body includes the spine, hips and pelvis, abdominal structures and also the proximal lower limb. According to them, the core musculature includes the muscles of the trunk and pelvis.[3] These muscles are responsible for the maintenance of stability of the spine and pelvis and help in the generation and transfer of energy from large to small body parts during many sports activities. So, in addition to its stabilizing function, the core musculature also has a mobilizing function.[3]

1.2 Core Stability

There is no single universally accepted definition of core stability. Panjabi[5] presented a conceptualization of core stability that is based on three subsystems: the passive spinal column, active spinal muscles and a neural control unit. Based on this conceptualization, Liemohn et al.[1] defined core stability as "the functional integration of the passive spinal column, active spinal muscles and the neural control unit in a manner that allows the individual to maintain the intervertebral neutral zones within physiological limits, while performing activities of daily living." Kibler et al.[3] defined core stability as "the ability to control the position and motion of the trunk over the pelvis, thereby allowing optimum production, transfer and control of force and motion to the terminal segment in integrated athletic, kinetic chain activities." Leetun et al.[6] stressed the importance of the passive structures to a lesser degree and stated that core stability can be seen as the product of motor control and muscular capacity of the lumbo-pelvic-hip complex. This definition stresses the importance of coordination in addition to core strength and endurance. Although the terms core stability and core strength are sometimes used interchangeably, core strength is just one part of the core stability concept and so the term 'core strength' is subsumed within the concept of core stability.

McGill and Cholewicki[7] formulated a biomechanical foundation for stability that gives useful insights in the complex interactions that are involved when stabilizing the core. Their theory was based on and elaborated on the work of Bergmark,[8] who mathematically formalized the concepts of energy wells, stiffness and stability. According to McGill and Cholewicki,[7] the foundation of core stability begins with the concept of potential energy.

For musculoskeletal application, the focus is mainly on elastic potential energy. Elastic bodies possess potential energy by virtue of their elastic deformation under load and this elastic energy is recovered when the load is removed.[7] The greater the stiffness, the more stable the structure. Thus, stiffness creates stability.[9] Joint stiffness increases rapidly and nonlinearly with muscle activation, so that very modest levels of muscle activity create sufficiently stiff and stable joints.[9] Furthermore, joints possess inherent joint stiffness through their ligaments and other capsular structures. These structures contribute to stiffness, which increases towards the end range of joint motion.[7] All stabilizing musculature must work coherently to achieve stability.[7]

For the purpose of their study, Zazulak et al.[4,10] developed a more operational definition. They defined core stability as "the body's ability to maintain or resume an equilibrium position of the trunk after perturbation."

It should be considered here that, while the focus of McGill and Cholewicki[7] is mainly on the anticipating reaction of the core structures during small, expected perturbations, Zazulak et al.[4,10] also assume greater, unexpected disturbances of the core, in which the creation of stiffness does not suffice to maintain stability. If the initial spine stability is insufficient in relation to the external load applied by a perturbation, a fast and strong reflex response can compensate, in order to constrain trunk motion within a safe boundary. Such a direction-specific muscle reflex response may be crucial in preventing large intervertebral displacements or buckling of the spine and subsequent damage of soft tissues under sudden loading conditions.[11]

1.3 Important Structures in Maintaining Core Stability

Lumbar spine stability is provided by bone, disc, ligaments and muscle restraints.[12] As noted above (section 1.2), stability of the lumbar spine requires both passive stiffness, through the osseous and ligamentous structures and active stiffness, through muscles.[2] If any of the active or passive components are impaired in function, instability of the lumbar spine may occur. It has been shown that the musculature is most important in maintaining spinal stability under various conditions.[12] Panjabi[5] suggested that muscle activity is used to compensate for a loss of passive stability. It has been shown that muscles can contribute to stability of the trunk through co-contraction.[13] Healthy subjects increase co-contraction in response to conditions that threaten spinal stability. This adaptation is triggered by information from both mechanoreceptors and nociceptors.[13] Co-contraction further connects the stability of the upper and lower extremities via the abdominal fascial system. This effect becomes particularly important in overhead athletes, because the created stable connection acts as a torque-counter torque of diagonally related muscles during throwing.[2] To acquire this co-contraction, precise neural input and output are needed. Arokoski et al.[14] identified that the stability of the spine was increased with either increased flexor-extensor muscle co-activation or increased intra-abdominal pressure. In the temporal sequence of many athletic tasks, core muscle activity precedes lower extremity muscle activity. Hodges and Richardson,[15] for example, demonstrated that trunk muscle activity often occurs before the activity of the lower extremity musculature. This implies that the CNS creates a stable foundation for movement of the lower extremities through co-contraction of particular muscles.[10]

Kavcic et al.[16] conducted a systematic biomechanical analysis in order to assess the potential stabilizing role of individual lumbar muscles. This study showed that, when loads are applied to the spine, there is an integration of the different muscles in order to maintain spinal stability and these control patterns change as the spine loading patterns change.[16] The same result was found by means of biomechanical analysis conducted by Cholewicki and McGill[17] and Cholewicki and VanVliet,[18] who suggested that no single muscle possesses a dominant responsibility in providing lumbar spine stability. Generally, those muscles that were antagonist to the dominant moment of the task were most effective at increasing stability.[16]

It appears that most trunk muscles are important in providing core stability, their importance depending on the activity being performed.[9] These include muscles that attach directly to the vertebrae: the uni-segmental multifidus muscles and multi-segmented quadratus lumborum and longissimus, and muscles that do not: iliocostalis and the abdominal wall. Across the various trunk muscles, the mechanical advantage to provide stability to the lumbar spine varies. It should be born in mind that this variety is functional. This can be illustrated by the example of a long-guyed mast. Guy wires, wires running from the top and a few levels below to the ground, are needed to keep the mast upright, but the mast should also have sufficient stiffness by itself to prevent buckling. In the back, these functions are provided by the global stabilization system (GSS) and local stabilization system (LSS), respectively.

1.4 Local and Global Muscle Systems

Comerford and Mottram[19] stated that all muscles have the ability to concentrically shorten and accelerate motion for mobility function, to isometrically hold or eccentrically lengthen and decelerate motion for stability function and to provide afferent proprioceptive feedback to the CNS for regulation and coordination of muscle function. Bergmark[8] proposed a classification scheme that groups core muscles into either the GSS or the LSS. The larger muscles of the trunk are the chief contributors to the GSS and the smaller muscles are the main contributors to the LSS. The LSS plays a major role in the coordination and control of motion segments, whereas the muscles of the GSS, which have larger masses and longer moment arms of force, provide more forceful movements.[1] The LSS muscles are closer to the spinal column and thus can provide varying degrees of segmental control. For example, the intertransversarii mediales, interspinales and rotators are very close to the centre of rotation of the spinal segments. Their high density of muscle spindles and their very small physiological cross-sectional area suggests that they may act primarily as position transducers of the spinal column.[20] Following the work of Bergmark,[8] Comerford and Mottram[19] have also proposed a classification system for muscle function. They have characterized muscles as local stabilizers, global stabilizers and global mobilizers. The function of the local muscle system is to provide sufficient segmental stability to the spine, whereas the global muscle system provides general trunk stabilization and enables the static and dynamic work necessary for daily living and sport activities.[21] A symmetrical activation of the local muscles has been shown during the performance of low load, asymmetric lifting tasks, which suggests that these muscles play a stabilizing role during these activities. The global muscles, however, show asymmetric patterns of activation during the same tasks, supporting their role of global stabilizers and prime movers.[21] It has been identified that the multifidus, transversus abdominis and the internal obliques are part of the local stabilizing system, whereas the longissimus thoracis, rectus abdominis and external obliques constitute a part of the global stabilizing system.[21]

Recent work has focused on the functional contribution of different trunk muscles to postural stabilization of the lumbar spine as well as their respective changes in the presence of acute and chronic pain. Although the sensory-motor control of spinal stability is provided in a mutual interaction among all muscles of the trunk, Ebenbichler et al.[12] described four major functional groups of muscles that contribute via different mechanisms to the postural stabilization of the spine: (i) local, paravertebral muscles that directly stabilize the segments of the spine; (ii) global, polysegmental, paravertebral muscles that balance external loads to minimize the resulting forces on the spine; (iii) muscles that contribute to pressure facilitation within the abdominal cavity, thereby providing global stabilization of the spine; and (iv) muscles that facilitate the pressure within the fascia tube system of the back.[12]

Cholewicki and VanVliet[18] reported that all trunk muscles, including abdominal as well as back musculature, contribute to core stability. The relative contributions of each muscle group continually change throughout an athletic task.[10] The abdominals serve as a vital component of the core. In particular, the transversus abdominis has received a lot of attention.[2] Contracting the transversus abdominis increases intra-abdominal pressure and tensions the thoracolumbar fascia. The thoracolumbar fascia is an important structure that connects the lower limbs (via the gluteus maximus) to the upper limbs (via the latissimus dorsi). It helps to form a 'hoop' around the abdomen, consisting of the fascia posteriorly, the abdominal fascia anteriorly and the oblique muscles laterally.[3] This way, a stabilizing corset effect is created. Together, the internal oblique, external oblique and transversus abdominis increase the intra-abdominal pressure inside the hoop formed via the thoracolumbar fascia, thus creating functional stability of the lumbar spine.[2] Contractions that increase intra-abdominal pressure occur before initiation of large segment movement of the upper limbs.[3] In this manner, the spine is stabilized before limb movements occur, thereby allowing the limbs to have a stable base for motion and muscle activation. Thus, abdominal muscle contractions help in creating a rigid cylinder, thereby enhancing stiffness of the lumbar spine. It is also important to note that the rectus abdominis and oblique abdominals are activated in direction-specific patterns with respect to limb movements, thus providing postural support before limb movements.[3]

According to Ebenbichler et al.,[12] the back muscles are clearly divided into two major groups: (i) the deep muscles of the lumbar spine that span one or a few segments including the multifidus muscle, the musculi rotatores lumborum, musculi interspinales and musculi intertransversarii mediales and laterales; and (ii) the long erector spinae muscles that span many segments.[12] These two distinct functional muscle groups have large differences in innervation, which indicates significant functional differences. The stabilizing role of the paravertebral muscles aims mainly at protecting the articular structures, discs and ligaments from excessive bending, strains and injury.[12] According to Bergmark,[8] the role of the long, multisegmental back muscles is to provide general trunk stabilization and to balance external loads, thereby helping to unload the spinal segments.

1.5 Hip Musculature

At the opposite end of the trunk component of the core muscles are the pelvic floor muscles. Most of the prime mover muscles for the distal segments (latissimus dorsi, pectoralis major, hamstrings, quadriceps and iliopsoas) attach to the core via the pelvis and spine. Most of the major stabilizing muscles for the extremities (upper and lower trapezius, hip rotators and glutei) also attach to the core.[3] Because of the difficulty in directly assessing these muscles, they are often neglected or ignored with respect to musculoskeletal rehabilitation. The glutei are stabilizers of the trunk over the planted leg and provide power for forward leg movements.[3] The hip musculature plays a significant role within the kinetic chain, particularly for all ambulatory activities, in stabilization of the trunk and pelvis and in transferring force from the lower extremities to the pelvis and spine.[2] Although some authors[2,3] include the glutei as part of the core, being an integral part of core functioning, in the present article these muscles are seen as connections between the core and the lower extremities. Kibler et al.[3] stated that the glutei, as major stabilizing muscles for the extremities, attach to the core, implying that they do not constitute part of the core.

1.6 Stability versus Mobility

According to Kibler et al.,[3] core muscle activity is best understood as the pre-programmed integration of local, single-joint muscles and multi-joint muscles to provide stability and produce motion. This integrated core muscle activity results in proximal stability for distal mobility.[3] There is a proximal to distal patterning of force generation and a proximal to distal patterning in the creation of interactive moments that move and protect distal joints. Interactive moments are moments at joints that are created by motion and position of adjacent body segments.[3] They are developed in the central body segments. Interactive moments are important for developing proper force at distal joints and for creating relative bony positions that minimize internal loads at the joint.[3] Anderson and Behm[21] stated that much is known about how muscles maintain static equilibrium, but little is known about how they maintain dynamic balance when exerting an external force. Exerting external forces while attempting to maintain dynamic balance forms the base of success in the majority of sports and it is a necessity in the activities of daily living.[21] The cost of coping with instability is an increase in co-contractions, which results in a decrease in external force. However, in many instances, the task could not be performed without this co-activation.[21] Thus, this stabilization process consists of establishing active muscular constraints to minimize the degrees of freedom within one or several joints and results in stabilization of the excessive mobility of the extremities.[21] 'Sufficient stability' is both a complex concept and a desirable objective for which optimal balance between stability and mobility is required. However, the objective is constrained by the need for a modest amount of extra stability to form a margin of safety, but not so much as to compromise the spine with the additional load.[9] The art, especially for athletes, is to enhance mobility, while at the same time preserving sufficient stability.

1.7 Strength, Endurance and Sensory-Motor Control

Cholewicki and McGill[17] demonstrated that, in most persons, sufficient stability of the lumbar spine is achieved with very modest levels of co-activation of the paraspinal and abdominal muscles. Thus, maintaining sufficient stability when performing tasks, particularly the tasks of daily living, is not compromised by insufficient muscle strength.[9] It has been shown that only a very small increase in activation of the abdominal muscles is required to stiffen the spinal segments (5% of maximal voluntary contraction for activities of daily living and 10% of maximal voluntary contraction for rigorous activity).[3] Furthermore, it has been suggested that back muscle contractions as low as 25% of maximal voluntary contraction are able to provide maximal joint stiffness.[22] A low percentage of maximal voluntary isometric contraction from the trunk musculature thus stabilizes the spine during normal movements. This implies that, alongside muscle strength, muscular endurance and, in particular, sensory-motor control are important aspects in providing sufficient core stability.[21] For example, the trunk flexor-to-extensor ratio may be as or more important than absolute strength and endurance, because this ratio has been shown to be abnormal in people with back pain.[23]

1.8 Sensory-Motor Control

In the last few decades, there has been an increasing awareness of the importance of the specialized and integrated action of the muscle system in maintaining stability and optimal function of the movement system. Efficient movement function and the maintenance of balance during dynamic tasks are more complex than merely adequate force production from the muscles. The muscle actions must be precisely coordinated to occur at the right time, for the correct duration and with the right combination of forces.[24] This coordinated action occurs within groups of synergistically acting muscles and is also important in the interactions between agonist and antagonist muscles. It requires sensory, biomechanical and motor-processing strategies along with learned responses from previous experience and anticipation of change.[24] A primary sensory mechanism for motor control is proprioception from the muscles. Gandevia et al.[25] stated that proprioception relates to three key sensations, namely sensation of position and movement of the joints, sensation of the perceived timing of muscle contraction and sensation of force, effort and heaviness of workload.

It is important to note that the dynamic stability of the body, or any specific joint such as the knee, depends on neuromuscular control of the displacement of all contributing body segments during movement.[10] Core stability is related to the body's ability to control the trunk in response to internal and external disturbances. These include forces generated from distal body segments as well as forces generated from expected or unexpected perturbations.[10] When a limb is moved, reactive forces are imposed on the spine acting in parallel and opposing those producing the movement.[12] Due to its multi-segmental nature and the requirement for muscle contraction to provide stability of the spine, the spine is particularly prone to the effect of these reactive forces. This indicates the importance of muscular control of the spine during limb movement.[12]

Radebold et al.[26] stated that, in general, there is a combination of three levels of motor control (spinal reflex, brain stem balance, and cognitive programming) that produces appropriate muscle responses. The first one, the spinal reflex pathway, uses proprioceptive input from muscle spindles and Golgi tendon organs. For the automatic control of the motion segment, the presence of a ligamento-muscular reflex has been proposed.[12] The γ-spindle system facilitates the α-motor neurons that control the slow twitch muscle fibres. The second level of motor control, the brain stem pathway, coordinates vestibular and visual input, thereby using proprioception from joint receptors.[26] Cognitive programming is based on stored central commands, which lead to voluntary adjustments.[26] Pre-programmed muscle activations result in so-called anticipatory postural adjustments.[3] These adjustments position the body to withstand the perturbations to balance created by the forces of actions such as kicking, throwing or running. Ebenbichler et al.[12] found that, when reactive forces due to limb movement challenged the stability of the trunk, some muscles contracted before the agonist limb muscle to compensate for the perturbing effect on posture. The anticipatory postural adjustments create the proximal stability for distal mobility, as mentioned earlier (section 1.6). The muscle activations also create the interactive moments that develop and control forces and loads at joints.[3]

Ebenbichler et al.[12] wrote about the presence of two parallel systems in the control of voluntary movements, one to control the intended voluntary element of the movement and one to initiate corrective forces necessary for maintaining equilibrium. It has been shown that there exists an inverse relationship between the length of the voluntary reaction time and the degree of postural stability in a certain situation.[12] A shorter reaction time for a specific task implies an increase in the postural stability. Findings from studies on trunk motor control demonstrated that the CNS immediately interrupts an ongoing voluntary motor programme to prioritize the postural control programme.[12] So, from these results, it can be concluded that appropriate muscle recruitment and timing is extremely important in the control of spine equilibrium and mechanical stability.

2. Core Stability, Athletic Performance and Injury

In an article by Leetun et al.,[6] it was stated that core stability has an important role in injury prevention. Decreased lumbo-pelvic stability has been suggested to be associated with a higher occurrence of lower extremity injuries, particularly in females. This highlights the importance of proximal stabilization for lower extremity injury prevention. In addition, Anderson and Behm[21] suggested that a lack of trunk stabilization may also be a major contributor to the occurrence of low back pain.

2.1 Core Stability and Athletic Performance

Besides its local functions of stability and force generation, core activity is involved in almost all extremity activities such as running, kicking and throwing. Since the core is central to almost all kinetic chains in sports activities, control of core strength, balance and motion will maximize all kinetic chains of upper and lower extremity function.[3]

A few studies have been found that investigated whether improved core stability is associated with better physical performance. Stanton et al.[27] did not find a positive relationship between core stability and running performance as measured by maximal oxygen uptake or running economy, nor did they find an improved posture during treadmill running to volitional exhaustion with increased core stability. In addition, Tse et al.[28] found no increased functional performance in college-aged rowers after exposing them to an 8-week core endurance training programme.

Considering the wide variety of movements associated with various sport activities, athletes must possess sufficient strength in hip and trunk muscles to provide stability in all three planes of motion.[6] More and more, scientists are including assessment of joint mechanics proximal and distal to the sites where injuries tend to occur. This is because of the closed chain nature of athletic activities. Motion at one segment will influence that of all other segments in the chain. However, the influence of proximal stability on lower extremity structure and pathology remains largely unknown.[6] Given the wide range of individuals and physical demands, questions remain as to what is the optimal balance between stability, motion facilitation and moment generation. And there are questions about how much muscular co-contraction is necessary to achieve stability and how it is best achieved.[9]

2.2 Core Stability and Injuries

Zazulak et al.[4] showed that proprioceptive deficits in the body's core may contribute to decreased active neuromuscular control of the lower extremity, which may lead to valgus angulation and increased strain on the ligaments of the knee. Such findings, in addition to years of empirical evidence, have led to the suggestion that the knee may be a victim of core instability with respect to lower extremity stability and alignment during athletic movements.[6] In particular, in reference to anterior cruciate ligament injuries, Ireland[29] described a so-called 'position of no return' that is characterized by hip adduction and internal rotation, which in turn leads to knee valgus and tibial external rotation. In addition, the same alignment tendency seems to be related to repetitive injuries such as patellofemoral pain syndrome and iliotibial band friction syndrome.[6]

With respect to direct injuries of the body's core, Nadler et al.[30] noted that athletes with acquired ligamentous injuries or lower extremity overuse were significantly more likely to require treatment for low back pain during the following year. In addition, various other factors have been shown to be associated with low back pain, under which are poor muscle endurance, altered muscle firing rates and muscular imbalance.[31] The occurrence of low back pain in an athletic population has been well documented in various sports, including football, golf, gymnastics, running, soccer, tennis and volleyball. Between 5% and 15% of all athletic injuries consist of low back pain.[32] Most sport injuries related to the lumbar spine are soft tissue injuries such as muscle strains, ligament sprains and intervertebral disc injuries.[32] These injuries often prevent the athlete from regular training and competition. Moreover, low back injuries have become an increasing problem, especially in relation to recreational activities with high demands on the back such as racquet sports, golf, handball, baseball, volleyball or rowing. In amateur athletes, these injuries often mean an end to those sporting activities and a prolonged disability to work.[33]

2.3 The Role of the Hip Musculature in Injury Occurrence

Some authors, who considered the hip musculature to be part of the body's core, have investigated several characteristics of the hip muscles in relation to the occurrence of lower extremity or low back injuries. Some of their results are discussed below.

In people with lower extremity instability or low back pain, poor endurance and delayed firing of the hip extensor (gluteus maximus) and abductor (gluteus medius) muscles have been identified.[31] With regard to muscular influences on low back pain, the hip musculature plays a significant role in transferring forces from the lower extremity towards the spine and thus may influence the development of low back injuries.[34] With respect to knee injuries, weak hip muscles are a common finding associated with knee injury. For example, weak hip abductors and tight hip flexors are seen in association with anterior knee pain.[3] Leetun et al.[6] have conducted a prospective study in which core stability measures were compared between athletes who reported an injury during their season versus those who did not. They looked for strength measures that could be used to identify athletes at risk for lower extremity injury. It was found that athletes who sustained an injury over the course of a season displayed significantly less hip abduction and external rotation strength than uninjured athletes.[6] Hip external rotation weakness most closely predicted injury status. These results are in accordance with the above described findings by Ireland,[29] who showed that hip abductors and external rotators play an important role in the alignment of the lower extremities. They assist in the prevention of movement into hip adduction and internal rotation during single limb support.

However, as Leetun et al.[6] also argued themselves, hip external rotation strength is only one element of core stability and other aspects not included in the study may also have predicted the occurrence of lower extremity injury, especially because of the low coefficient of determination that was found for the hip external rotation strength.

2.4 Strength versus Endurance

In section 1 of this article, it has been shown that besides muscular strength, endurance and especially sensory-motor control are very important aspects in providing sufficient core stability. Let us first have a look at the endurance aspect.

Ebenbichler et al.[12] stated that decreased trunk muscle extensor strength has often been associated with low back pain, but also back muscle endurance appears to be reduced in patients with acute and chronic low back pain. McGill et al.[35] suggested that trunk muscle endurance is of greater importance in the prevention of low back pain than the ability of these muscles to generate force. In agreement with this suggestion, the endurance of the trunk extensors has been found to predict the occurrence of low back pain in 30- to 60-year-old adults.[6] However, it has to be said that the amount of muscle activation needed to ensure sufficient stability depends on the task.[35] Generally, for most tasks of daily living, very modest levels of abdominal wall co-contraction are sufficient. But if a joint has lost passive stiffness due to damage, more co-contraction is needed to compensate for the deficiency. Besides, when encountering unpredictable activities such as a sudden load to the spine, a fall or quick movements, a strength reserve is needed. In sport activities and during heavy physical work, there are increased demands on both strength and endurance.[36] However, according to McGill,[9] a review of the evidence suggests that greater ranges of spine motion are associated with increased risk of future problems and that endurance, more than strength, is related to reduced symptoms.

2.5 Spinal Instability Caused by Neuromuscular Imbalance in the Local Muscle System

In section 1 of the present article, a distinction between the local and the global muscle system has been observed. Dysfunction of movement around a joint can be a local or a global problem,[8] although both frequently occur together.

Local problems can be caused by a dysfunction of the recruitment and motor control of the deep segmental stability system resulting in poor control of the neutral joint position.[36,37] The motor recruitment deficits present in two ways, namely altered patterns of recruitment and altered timing (a delay in muscle response time). Panjabi[38] described instability of a joint or motion segment in terms of a lack of dynamic muscle control of the neutral zone, resulting in an abnormal increase in the range of motion. He defined the neutral zone as the range of intervertebral motion within which there is minimal internal resistance.[38] It is hypothesized that changes in a spinal segment that allow for excessive motion cause poor spinal stability and back pain. Structural changes that contribute to this instability are, among other things, disc disease, muscular changes such as weakness and poor endurance and ineffective neural control.[39] With respect to muscular changes, a significant reduction of cross-sectional area has been demonstrated in various local muscles, which is supposed to be associated with either failure of normal recruitment or with atrophy of the muscle.[24] Excessive motion of the lumbar segment results in the loss of sensory-motor control in a spine's segment neutral zone. So an increased neutral zone has been suggested as an indicator of clinical instability, although no objective quantitative measurements for clinical use are currently available to assess this indicator.[12] To maintain mechanical stability of the lumbar spine, compensation is required by the trunk musculature. It has been shown that effective muscle control can return the neutral zone within physiological limits.[12]

2.6 Spinal Instability Caused by Neuromuscular Imbalance in the Global Muscle System

So far, we have only considered neuromuscular dysfunctions in the local muscle system, but functional stability is dependent on integrated function of both the local and global muscles. Mechanical spinal stability dysfunction can occur in the form of segmental (articular) or multi-segmental (myofascial) dysfunction. These dysfunctions present as combinations of restriction of normal motion and compensations to maintain function.[19]

The role of the global spinal muscles is to control range of movement and alignment. Dysfunction of these muscles is caused by an imbalance in recruitment and length between the mono-articular stability muscles and the bi-articular mobility muscles.[24] Comerford and Mottram[24] noted that there are many clinically consistent neuromuscular imbalances between synergistic and antagonistic muscles. These are characterized by the early and dominant recruitment of the multi-articular mobilizing trunk muscles, while the mono-articular stabilizing synergist recruitment is delayed or these muscles lack efficiency in their shortening capacity. This imbalance can result in abnormal over-pull and under-pull by the muscles around a motion segment, so that there is give (excessive joint motion) in the direction of over-activity and restriction (a loss of joint motion) in the direction of the less active global muscles.[19,24] The result of this faulty movement is abnormal accessory glides, which increase micro-trauma in the tissues around the joint, leading to dysfunction and pain.[19] In the normal functioning musculature, there exist complex motor control processes that regulate relative stiffness or flexibility in linked multi-chain movements.[24] The movement system has a great ability to adapt to changes. When significant restriction of motion occurs at a joint, the body will attempt to maintain function at all costs. To achieve this, some other joint or muscle must compensate by increasing relative mobility, which often results in tissue damage.[24] In summary, dysfunction in the global system presents in three interrelated forms, namely length-associated change related to muscle function, imbalance in recruitment between synergistic and antagonistic muscles and direction-dependent relative stiffness and compensation.

2.7 Sensory-Motor Control and Injuries

Now that we have seen the importance of sensory-motor control in providing stability, let us consider what is known about the relationship between deficient core neuromuscular control and the occurrence of injuries.

In all activities of daily living, a human body is moved through three dimensions at differing velocities while experiencing varying torques and forces. Especially in sport activities, great demands are placed on the strength, endurance and coordination of the system. An inefficient neuromuscular system may not adapt well to these demands, resulting in impaired performance or even injury.[21] We have seen that spinal muscles provide stability and that muscle recruitment patterns significantly affect loading on the intervertebral joints. Imbalanced muscle activation can lead to inappropriate magnitudes of muscle force and stiffness, thereby loading the spine incorrectly and inducing low back pain and musculoskeletal injury.[9] Brown and McGill[40] stated that, under conditions of static equilibrium, the stiffness produced by a muscle will function in a stabilizing manner, while its force can function in either a stabilizing or destabilizing manner, depending on the orientation of the muscle about the joint. Considering that the relationship between force and stiffness is non-linear and a situation in which the orientation of a muscle is such that its instantaneous tension acts in a destabilizing manner about a joint, there may exist a critical force level at which any additional increase in force becomes dominant over the corresponding stiffness increase, thereby reducing the stabilizing potential of the muscle.[40] Comerford and Mottram[24] stated that there is a clear link between reduced proprioceptive input, disturbed slow motor unit recruitment and the development of chronic pain states. Deficient core neuromuscular control may predispose athletes to low back injuries as well as injuries of the lower extremity.

With respect to low back problems, a delayed reflex response of trunk muscles is found to be a pre-existing risk factor for sustaining a low back injury in athletes.[10] Furthermore, because >90% of sports-related low back injuries occur from self-initiated actions such as jumping, running or cutting, it is likely that a deficit in motor control is a causative factor in these injuries.[32] This statement is supported by the findings of Gill and Callaghan,[34] who reported a significant decrease in repositioning ability in patients with low back pain. They concluded that precise muscle spindle input is a vital aspect for accurate positioning of the pelvis and lumbo-sacral spine.[34] In addition, subjects with low back pain have been shown to demonstrate impaired postural control, delayed muscle reflex responses following sudden trunk unloading and abnormal trunk muscle recruitment patterns.[10] Furthermore, athletes with a history of low back pain continued to demonstrate motor control deficits of the trunk, even after clinical recovery and return to their prior level of competition.[10]

With regard to knee injuries, Zazulak et al.[10] showed that decreased neuromuscular control of the body's core, measured during sudden trunk unloading and trunk repositioning tasks, is associated with an increased risk of knee injury in athletes. Dynamic stability of an athlete's knee is defined as the ability of the knee joint to maintain intended trajectory after internal or external disturbance.[10] It depends on accurate sensory input and appropriate motor responses to deal with rapid changes in trunk position during manoeuvres such as cutting, stopping and landing. Deficits in neuromuscular control of the body's core may compromise dynamic stability of the lower extremity, resulting in increased abduction torque at the knee.[10] As a result of this, strain on the knee ligaments is increased, leading to injury.

In the study by Zazulak et al.,[10] the strongest predictor of injury in the female athletes was found to be the magnitude of displacement, in particular laterally, during sudden trunk unloading. In addition, active proprioceptive repositioning error and history of low back pain were also related to a higher risk of sustaining a knee injury.[10] Zazulak et al.[4] reported deficits in active proprioceptive repositioning in women with knee injuries and ligamental or meniscal injuries, compared with uninjured women. These deficits are measured prospectively, indicating that they may predispose female athletes to knee injury. In contrast, no differences in proprioceptive repositioning error were found between injured and uninjured men.[4]

Thus, in female athletes, impaired core proprioception may lead to impaired control of the core, which in turn negatively affects control of the knee and consequently may lead to knee injury.[4] With respect to male athletes, Zazulak et al.[10] found that the core proprioception deficits were only significant knee injury predictors for the ligament-injured group. In this group, history of low back pain was shown to be the strongest predictor of knee injury.[10]

3. Core Stability, Neuromuscular Core Control and Balance

In section 2, we have seen that dysfunction of spinal structures, dysfunction of trunk muscles or neuromuscular deficits can result in spinal instability. Instability of the spine is an important aspect of low back pain, since it can lead to excessive tissue strain and consequent pain.[14] Comerford and Mottram[24] stated that the muscles in the local system do not demonstrate consistent strength deficits or changes in length. The importance of the neural control over the trunk muscles was underlined by Barr et al.,[39] who noted that back pain has been found to be associated with deficits in spinal proprioception, balance and with deficits in the ability to react to unexpected trunk perturbation. We have also seen before that deficits in neuromuscular control of the body's core may lead to uncontrolled trunk displacement during athletic movement. This, in turn, may increase knee abduction motion and torque, place the lower extremity in a valgus position and result in increased strain on the knee ligaments and in anterior cruciate ligament injury.[10] Sections 3.1-3.4 discuss the relationship between impaired muscular core control, poor balance performance and spinal stability, by considering various results of EMG and balance studies, mainly conducted in patients with low back pain.

3.1 Delayed Muscle Reflex Response in Patients with Low Back Pain

Deficiencies in motor control of the lumbar spine have been proposed as one of the factors predisposing a person to experience a low back injury. This is supported by findings that patients with low back pain, who were being exposed to sudden trunk loading, exhibited longer trunk muscle response latencies than healthy controls.[41] In addition, Ebenbichler et al.[12] noted that the timing of feed-forward contractions of the abdominal muscles in preparation of an arm movement task seems to be disturbed in these patients. Whereas healthy subjects tend to contract the transversus abdominis before other muscles to stabilize the spine in anticipation of limb movement, patients with low back pain show a delayed contraction of this muscle.[36] Radebold et al.[42] and Cholewicki et al.[32] measured reflex responses from 12 major trunk muscles during sudden force release experiments in subjects with chronic low back pain and in athletes with a history of an acute low back injury. These responses were short-latency reflexes most likely associated with muscle spindle activity. It was shown that subjects with low back pain had significantly longer latencies, both in the offset of agonistic and in the onset of antagonistic muscles.[32,42] These longer latencies were seen in response to sudden force release in flexion, extension and lateral bending directions. In comparison with healthy controls, the individual muscle reaction times of the patients showed greater variability.[42] In addition, Cholewicki et al.[32] also found that athletes with a recent history of an acute low back injury shut off significantly fewer muscles. This was supported by the findings of Cholewicki et al.[41] that athletes with low back injuries shut off a significantly smaller number of muscles in trunk flexion. Furthermore, athletes with a history of low back injury switched on a smaller number of trunk extension muscles than athletes without such a history. The results of Cholewicki et al.[41] also showed that delayed switch-off latencies of the abdominal muscles in flexion and lateral bending are a significant predictor of a future low back injury in athletes. All these results enhance our understanding of the mechanisms underlying low back injuries. They are in favour of the hypothesis that a delayed muscle reflex response increases the vulnerability of the spine to injury under sudden loading conditions.

An alternative to the hypothesis of delayed muscle reflex response as a risk factor is the hypothesis that the delayed response is caused by the injury or pain itself. Damage to the receptors within the soft tissues of the lumbar spine could impair the feedback control and in turn delay the reflex response.[41] Another alternative is the hypothesis that the delayed muscle reflex is a compensation mechanism, adopted by the patient with low back pain to compensate for an injured and unstable spine or to avoid pain. However, Cholewicki et al.[41] found no significant change in muscle reflex latencies following a low back injury among athletes who reported no history of injury, indicating that delayed muscle response to sudden trunk loading is a significant predictor of a future low back injury.

3.2 Neuromuscular Imbalance in Patients with Low Back Pain

An adequate response to sudden loading depends also on correct muscle recruitment patterns to assure the mechanical stability of the lumbar spine.[42] Besides altered timing, motor control deficits also present as altered patterns of recruitment. Comerford and Mottram[24] stated that there is evidence of alteration of normal recruitment, both in peripheral and in local trunk stability muscles, which is associated with pain or pathology. These alterations are present under normal functional movement conditions. The only consistent evidence of failure of the muscles in the local system is in the regulation of muscle tension to control segmental motion and to recruit prior to loading of the joint system, thereby enhancing stability during function.[24] The end result of this altered recruitment pattern is a loss of functional or dynamic stability. Renkawitz et al.[33] found distinct neuromuscular imbalances between right and left erector spinae at the lumbar level during maximum voluntary trunk extension among athletes with low back pain, whereas there were no significant EMG-activity imbalances in subjects without low back pain. These results support the hypothesis that neuromuscular imbalance is associated with low back pain, especially in athletes participating in sports with high demands on the back. However, Renkawitz et al.[33] also stated that not every neuromuscular imbalance is a pathological finding. For achieving top athletic performance, unilateral neuronal and muscular adjustments are sometimes important preconditions. Van Dieën et al.[13] conducted a study in which trunk muscle recruitment patterns in patients with chronic low back pain were compared with those in healthy control subjects. They found that the ratios of antagonist over agonist and the ratios of lumbar over thoracic erector spinae EMG amplitude were greater in the patients than in the control subjects.[13] In addition, Radebold et al.[42] demonstrated a significantly different muscle recruitment pattern in response to sudden load release between patients with chronic low back pain and healthy control subjects. The patients maintained agonistic muscle contraction while their antagonistic muscles became concurrently activated, whereas the electromyograms of healthy control subjects showed a switch from agonistic to antagonistic muscle contraction, not exhibiting co-contraction in muscle recruitment patterns. Furthermore, patients showed large variability in the recruitment pattern of individual muscles compared with the healthy control group.[42]

Without a prospective study it is hard to answer the question whether neuromuscular imbalances are a result or a cause of low back pain. In their study, Radebold et al.[42] considered the differences exhibited within the chronic low back pain group to represent specific muscle response patterns, necessary as a compensation mechanism to stabilize their lumbar spine in response to sudden loading. In addition, Van Dieën et al.[13] suggested that the changes in muscle activity in patients with low back pain should be regarded as functional adaptations in response to a reduced spinal stability. But even if the muscle co-activation pattern after sudden loading is an adaptation mechanism, it also is an indicator of abnormal function for which the individuals need to compensate.[32]

3.3 Balance Performance in Relation to Core Stability

Now that the relationship between neuromuscular control and core stability has been discussed, let us now consider what is known about balance performance in relation to core stability and neuromuscular core control. Maintenance of balance in upright posture is essential in practicing daily activities and sports, also with respect to the prevention of injury. Stabilization of the trunk is crucial for maintaining static or dynamic balance, especially to provide a solid base when attempting to exert forces upon external objects.[21] However, there is little research documenting the effects of balance on performance measures such as, for example, force and power.

Within the human body there are a number of neuromuscular mechanisms that are responsible for the maintenance of balance. Balance is achieved through an interaction between central anticipatory and reflexive actions and these actions are assisted by the active and passive restraints caused by the muscular system.[21] There exist continuous afferent and efferent control strategies within the sensory motor system, using feedback from somatosensory, vestibular and visual inputs, with the vestibular system being considered as the main controller.[21] Standing on an unstable support calls upon higher levels of the control system and requires an essential change in the mode of utilization of incoming proprioceptive information. Kornecki et al.[43] reported that, when standing on an unstable support, the myopotentials of the stabilizing muscles precede the instant of force application. Slijper and Latash[44] reported such an anticipatory increase in activity of, among other muscles, the erector spinae and the rectus abdominis. These anticipatory postural adjustments minimize the subsequent postural destabilization. Two mechanisms are proposed to underlie the negative effect of postural instability on balance, namely an alteration of proprioceptive messages at the peripheral level and alterations in central processing.[21] Spinal proprioception and balance have been found to be abnormal in patients with chronic low back pain.[45,46] In addition, postural stability and one-foot balance have been found to be significantly reduced in these patients, suggesting that they possess poor central and peripheral balance control mechanisms.[12]

3.4 Relationship between Balance Performance and Neuromuscular Core Control

Only one study[26] has been found examining the relationship between balance performance and trunk muscle properties. In this study, it was investigated whether trunk muscle response to quick force release was correlated with balance performance in unstable sitting. It was shown that patients with chronic low back pain have poorer postural control of the lumbar spine than healthy control subjects and this difference increased with increasing task level. Most importantly, in the absence of visual feedback, poor balance performance correlated significantly with longer trunk muscle onset times in response to sudden force release. The authors noted that this finding suggests the existence of a common pathology underlying both phenomena.[26]

In this study by Radebold et al.,[26] two different motor control pathways were addressed, namely the spinal reflex and the brain stem pathway. These pathways are both dependent on proprioception and other sensory inputs, on central information processing and on appropriate motor output. It is quite likely that poor postural control and delayed muscle response are due to a deficit in one or more of these components.[26]

The significant correlation between the average muscle onset time and balance performance was only found in the eyes closed condition. The more pronounced deficiency in postural control during this condition was suggested to exist because of the remaining sensory input systems being more challenged in the absence of visual feedback.[26]

It is also interesting to note that the healthy control subjects controlled their posture better in the sagittal plane than in the lateral direction, although the patients with low back pain showed no difference between the two directions.[26] It was suggested that fine postural adjustments might be easier in the sagittal plane, because all joints have a much greater range of motion or even move exclusively in that direction. However, in the case of a disturbed proprioception, as in patients with low back pain, those subtle differences may disappear. Therefore, balance performance, measured in the anterior/posterior direction, might best discriminate between patients with low back pain and healthy control subjects.[26]

4. Training Core Stability

Strength and endurance of the trunk musculature and torso balance are said to be important for core stability, appropriate posture and maximal performance during sports.[47] To enhance athletic performance and to prevent or rehabilitate various lumbar spine and musculoskeletal disorders, strengthening or facilitation of the core muscles has been advocated.[2] There is a need to develop exercise programmes and therapeutic strategies based on academic and clinical evidence. Although the use of core strengthening programmes is widespread, little research has been conducted on the efficacy of these programmes. The goal of core stability exercise programmes is enabling performance of high-level activities in daily life and sports, while keeping the spine stabilized.[39]

In sections 4.1-4.3, some proposals are highlighted about what aspects of the core should be trained and how to train them. Subsequently, the importance of proprioceptive training will be discussed with special attention towards the role of Swiss ball training in improving core stability.

4.1 Functional Training of Both the Local and Global Muscle System

Rehabilitation strategies include specific mobilization of articular and connective tissue restrictions to regain myofascial extensibility.[19] Retraining of the global stability muscles is required to control myofascial compensations and the local stability system should be trained for appropriate muscle recruitment to control segmental motion by increasing muscle stiffness.[19] Besides the deep and the global musculature, other components that can be improved by exercise include muscles that increase intra-abdominal pressure to increase lumbar stability and the precise neural control of the lumbar muscles so that they fire in a normal and efficient manner.[39] The focus of core stability training should be on the integration of local and global stabilizer muscles, which is important to control the neutral joint position.[19]

One of the greatest challenges in training the core is the integration of specific training regimens into functional activities. Isolation of specific muscles or joints should be avoided in core stabilization exercises and the emphasis should be on the training of muscle activation sequences in functional positions and motions.[3] This way, normal biomechanical motions are restored through normal physiological activations. The eventual goal is to make the required muscle recruitment automatic and to achieve an adequate coordination of activation of the segments that are part of the kinetic chain.[3]

4.2 Core Strengthening: Coordinative and Proprioceptive Training

Anderson and Behm[21] noted that resistance training, besides its effect of increasing muscular strength, also increases the coordination of synergistic and antagonist muscle activation, thereby improving stability. It is known that strength gains can be due to both increases in the cross-sectional area of the muscles involved and due to improvements in neuromuscular coordination. The neural adaptations occurring in the early phase of a resistance training programme lead to an improved coordination of stabilizing muscles.[21] Comerford and Mottram[19] stated that motor control and recruitment are the priority in stability retraining. In addition, Akuthota and Nadler[2] stated that motor relearning may be more important than strengthening in patients with low back pain. Emphasizing the improvement in neuromuscular function of the trunk muscles may have positive effects with respect to the prevention of repeated injuries to the lower back or in reducing recovery time.[32] Furthermore, Hewett et al.[48] suggested that neuromuscular core training would also improve dynamic stability of the knee joint. Zazulak et al.[4] stated that there is strong evidence for the use of neuromuscular training to improve neuromuscular control of the trunk and lower extremity. Research by Caraffa et al.[49] showed that neuromuscular control can be enhanced by joint stability exercises, balance training, perturbation training, plyometric or jump exercises and sport-specific skill training. Perturbation programmes challenge the propriocepsis, for example by using wobble boards, roller boards, discs and Swiss balls. The sensitivity of afferent feedback pathways is increased through balance and motor skill training. By improving the sensitivity of the position sense of muscle and joint receptors, the onset times of stabilizing muscles is improved.[21] Wilder et al.[50] showed that, after a rehabilitation lasting only ***2*** weeks in which the back extensors were actively trained, muscle reaction times in patients with chronic low back pain decreased significantly down to a level similar to that of healthy volunteers. In addition, Hides et al.[51] found that patients with acute low back pain who received training in co-contracting the multifidi and transversus abdominis muscles had much less chance of recurrence of low back pain than a control group who did not receive this training. Renkawitz et al.[33] found that both the number of tennis players with low back pain and the occurrence of neuromuscular imbalance in the lumbar region decreased significantly as a result of dynamic neuromuscular changes after a sport-specific home exercise programme lasting 7 weeks. Based on these findings, it may be helpful to evaluate athletes for proprioceptive deficits before competition and to target them for specific active neuromuscular training when needed.

4.3 Swiss-Ball Training

Training on labile surfaces will challenge the musculature and by training the body to handle unexpected perturbations, balance and proprioception may improve.[2] Unstable training environments stress the stabilizing role of the musculature at the expense of functional force production. The goal of such training methods is to accommodate to an unstable environment, thereby diminishing the loss of force.[21] Numerous training aids have been developed to create a training environment in which functional performance can be enhanced, one of them being the so-called Swiss ball. Several studies have been conducted on the effectiveness of Swiss-ball training with respect to the improvement of core stability. Marshall and Murphy[52] found increased activity of the rectus abdominis, transversus abdominis and the internal obliques while performing different core stability exercises (single-leg hold and press-up) on a Swiss ball, compared with exercising on a stable surface. In addition, Behm et al.[53] showed an increase in the activation of the deep abdominal, stabilizers as well as the lumbo-sacral and upper lumbar erector spinae during trunk strengthening exercises on a Swiss ball. Besides the increase in EMG activity, Cosio-Lima et al.[47] also demonstrated an improved performance on a static balance task after a 5-week functional training programme with a Swiss ball compared with conventional floor exercises in untrained women. Stanton et al.[27] assessed certain strength and endurance aspects of the core as measured by the Sahrmann test (see section 5 for further description) and it appeared that 6 weeks of Swiss-ball training significantly improved performance on the test. From these findings, it can be concluded that the use of unstable surfaces such as a Swiss ball stresses the propriocepsis and increases the extent of activation of the trunk muscles that are important for balance and stability in sport.

5. Measuring Core Stability

This section looks at the various ways in which core stability has been assessed in the past few years. Usually doctors and therapists manually perform clinical testing of segmental spine stability,[12] but to date no objective quantitative measurements are available for clinical use. In section 1 of this article, we have seen that some authors stress the importance of muscular strength in providing core stability. Kibler et al.[3] stated that no standard way has been described to measure core strength. Section 5.1 discusses some issues related to the measurement of core strength and endurance and subsequently, various methods will be presented in which neuromuscular control and coordination of the muscles around the lumbar spine have been assessed in the past few years.

5.1 Measuring Core Strength and Endurance

Several investigators have used different techniques in trying to determine the relative strengths of specific core muscles via isometric dynamometer values and EMG data.[3] These data can give an estimate of core strength. Evaluation of any specific single muscle as a reference point is questionable because, to provide core strength, numerous muscles fire in task-specific patterns. In their review, Kibler et al.[3] proposed to assess core strength by qualitatively looking at one-leg standing balance ability and a one-leg squat and by conducting a standing, three-plane core strength test. Three-plane core testing is an attempt to quantify control of the core in the different planes of spine motion.[3] Patients stand, either on one leg or on both legs, a given distance away from a wall. Starting from different initial positions, they have to slowly move their body toward the wall, without hitting it. Reduced ability to maintain single-leg stance and reduced ability to just barely touch the wall are associated with decreased core strength.[3] Although clinical experience has demonstrated that this battery of tests gives useful information, allowing the design of specific rehabilitation protocols for increased core function, no specific studies have been conducted to determine reliability and validity of the three-plane core strength test.[3]

Therapy should focus on the muscles working in the planes of motion that are found to be deficient.[3] The observation of posture is of additional value with respect to specific flexibility and strength testing. Patients should be evaluated for common muscle imbalances that affect the ability to maintain a neutral spine position.[39] For this purpose, the use of ultrasound or fine-needle EMG may become of great value, although it has to be noted that this measurement method is very impractical to use in a clinical setting. There is no consensus about the question whether strength testing of the abdominals and spine extensors is clinically valuable. One reason for this variability in the literature may be the different strength requirements that patients have.[39]

With respect to the measurement of trunk muscle endurance, Stanton et al.[27] conducted a study in which subjects were required to adopt a push-up position with the elbows locked and the toes placed on the vertical apex of a Swiss ball, so that the subject was parallel to the ground. When the hip flexion angle reached a deviation of >10° from the angle determined at the start of the test, the time of failure was recorded. In addition, a clinical measure of the strength and endurance capacity of the core was obtained using the Sahrmann core stability test.[27] During this test, while the subject is lying supine, an inflatable pad of a Stabilizer Pressure Biofeedback Unit is placed in the natural lordotic curve and is inflated to 40mmHg. The test consists of five levels in which the subject has to make certain leg movements, with each level increasing in difficulty. During each level, the pressure on the Biofeedback Unit is noted and a deviation of >10mmHg from a particular baseline value indicates that lumbo-pelvic stability is lost.[27]

Kavcic et al.[54] conducted a study of which the purpose was to quantify tissue loading characteristics and lumbar spine stability resulting from the muscle activation patterns that were measured when selected stabilization exercises were performed. During the investigation, ten male subjects performed a series of eight different exercises, while external forces, 3-dimensional lumbar motion and electromyography were measured. In order to calculate a measure of L4-L5 compression and spine stability, the measured data were input into a series of biomechanical models. The value for stability (stability index) was obtained by calculating a level of potential energy in the lumbar spinal structure for each of the 18 degrees of freedom (three rotational axes at six lumbar joints). This stability index resulted from the combined potential energy existing in both the passive and active spinal structures, minus any work added by external loads. This way, 18 values of potential energy were obtained that were formed into an 18x18 Hessian matrix and diagonalized. The index of spine stability was represented by the determinant of this matrix. Based on this index, together with muscle activation levels and lumbar compression, Kavcic et al.[54] produced a rank order of the various stabilization exercises they had selected.

5.2 Measuring Neuromuscular Control and Coordination

As mentioned in section 1 of this article, sensory motor control of the tissues around the lumbar spine plays an important role in providing core stability. In their study, Marshall and Murphy[52] considered optimal stabilization to be increased muscle activation of the ventrolateral abdominals compared with the rectus abdominis activation. They calculated the ratio of the ventrolateral abdominal and erector spinae muscle activity expressed relative to the rectus abdominis, based on the percentage of maximum voluntary contraction, to determine the synergistic relationship between these muscles.[52] Liemohn et al.[1] conducted a study of which the major purpose was to develop a measurement schedule, enabling quantification of core stability. They noted that coordination and balance are key elements in core stability training activities and so they chose to measure core stability through balance tests in which actual core stability training postures were replicated.[1] For this purpose, a stability platform was used on which balance had to be maintained in three different postures, namely kneeling arm raise, quadruped arm raise and the bridging posture. The duration of the balance tasks was 30 seconds and the tilt limits of the balance board were set at 5° to either side. The number of seconds that the subject could not maintain balance within the range of the tilt limits was recorded.[1] Radebold et al.[26] also assessed core stability through a balance task, namely an unstable sitting test. Subjects were placed on a seat equipped with a foot support, thereby preventing movement of the lower extremities (Figure 1). Polyester hemispheres of varying diameter were attached underneath the seat, providing four levels of seat instability. The seat was placed on a force plate at the edge of a table. Displacements of the centre of pressure underneath the seat were measured with the force plate, while the subjects performed trials with eyes open and closed. The sitting task was chosen to verify that deficits in the postural control mechanism could still be identified when the lumbar spine was studied in isolation from the postural control of lower body joints. This test was designed to assess the brain stem postural control pathway.[26]

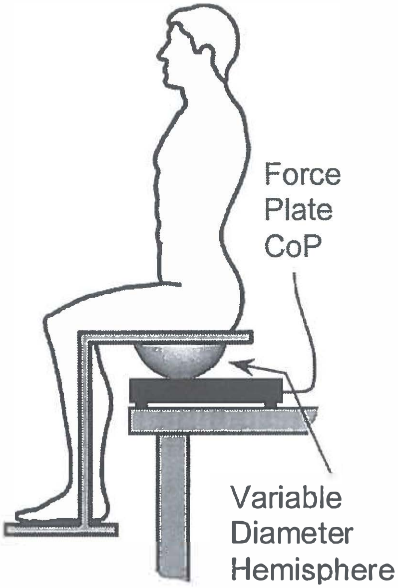

Figure 1. Sitting balance task. The subject is seated while arms and legs are fixed so that postural adjustments are only possible through trunk motion. The seat instability level is increased by decreasing the diameter of the hemisphere on the bottom of the seat. Displacements of the centre of pressure underneath the hemisphere are measured using a force plate (reproduced from Radebold et al.,[26] with permission).

The same authors[26] also used a test to assess the spinal reflex motor control pathway. During this test, subjects were placed in a semi-seated position in an apparatus that prevented motion of the lower extremities (Figure 2). They exerted isometric trunk flexion, extension and lateral bending at a force level corresponding to 30% of maximal isometric trunk exertion. Subsequently, the resisted force was suddenly released with an electromagnet and the agonistic and antagonistic response time of 12 major trunk muscles (rectus abdominis, external and internal oblique, latissimus dorsi, thoracic and lumbar erector spinae) was measured using surface EMG.[26] Agonistic muscles were defined as muscles that are active before the force release and are expected to shut off after the release. Antagonistic muscles are inactive before the force release and are expected to respond with increased electrical activity after the release.[41] In addition to the EMG equipment, Zazulak et al.[10] used a Flock of Birds electromagnetic device to record trunk motion after the force release. The sensor was placed on the back at approximately the T5 level. Although the semi-seated position is not a functional athletic position, this posture was chosen to control for other potential neuromuscular response strategies by movement around the lower extremity joints.[26]

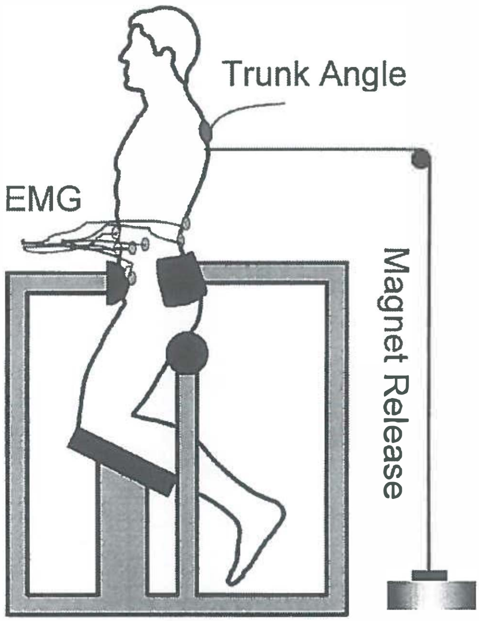

Figure 2. Trunk perturbation task. While the subject exerts isometric trunk flexion, extension or lateral bending, the resisted force is suddenly released by an electromagnet. Response times of 12 trunk muscles are measured using surface electromyography [EMG] (reproduced from Radebold et al.,[26] with permission).

In controlling the muscles around the lumbar spine, adequate core proprioception is of vital importance. Zazulak et al.[4] directly assessed core proprioception by measuring both active and passive proprioceptive repositioning using an apparatus designed to quantify trunk proprioception. The apparatus produced passive motion of the lumbar spine in the transverse plane. Subjects were seated on this apparatus so that rotation took place around a vertical axis extending through the L4/L5 vertebrae. The seat was driven by a stepper motor at a steady, slow rate, thereby minimizing tactile cueing. The focus of the test was mainly on feedback from muscular and articular mechanoreceptors of the trunk.[4] Since the upper body remained fixed to the backrest with a seatbelt, the contribution of the vestibular system was eliminated. The lower body moved in the plane parallel to the ground. Subjects were initially rotated ($2°\cdot s^{-1}$) 20° away from the neutral spine posture and stayed in that position for 3 seconds. In the passive test, the subjects were slowly rotated ($1°\cdot s^{-1}$) back towards the original position by the motor. In the active test, the subjects rotated themselves after the clutch was disengaged from the motor drive. When the subjects perceived themselves to be in the original, neutral position, they stopped the apparatus by pressing a switch and subsequently the repositioning error was recorded.[4] In the active test, trunk muscles generate the movement and therefore muscle spindle feedback is involved. However, during the passive test, when muscles are not active, sensory feedback from muscle spindles is decreased.[4] Therefore, input from joint and cutaneous receptors likely plays a greater role in sensory feedback during passive repositioning. Hence, the level of input from the muscle spindles differed between the active and passive tests.[4]

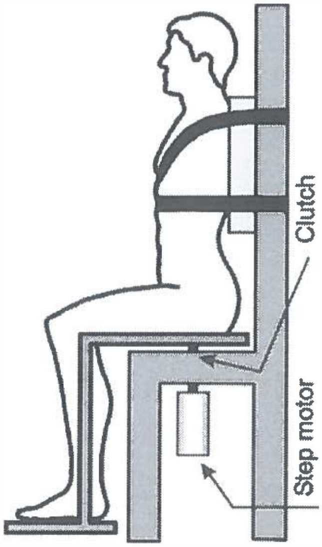

Figure 3. Proprioceptive repositioning task. The lower body of the subject is rotated in the transverse plane, 20° away from the neutral spine position. Subsequently, the subject is either rotated back to the neutral spine position (passive condition), or he rotates himself back to the neutral spine position (active condition). Eventually, the repositioning error is recorded in degrees (reproduced from Zazulak et al.,[4] with permission).

6. Concluding Remarks and Recommendations for Further Research

The purpose of this article was to give an overview of the existing literature with respect to several issues associated with core stability. In defining the core, it was found that some authors include the hip musculature as being part of the core, while most authors only concentrate on the musculature surrounding the lumbar spine. For the facilitation of discussion about other issues related to the core, it is proposed to leave the hip musculature out of consideration with respect to the concept of core stability, although the hip musculature is found to be very important in connecting the core to the lower extremities and in transferring forces from and to the core. In section 1 of this article, it was found that co-contraction of the trunk muscles, thereby creating stiffness which in turn creates sufficient stability, is very important in providing core stability. Besides stiffness, direction-specific muscle activations are also important in providing core stability, particularly when encountering sudden perturbations. The contributions of the various trunk muscles depend on the task being performed. Particularly for athletes, it is of great significance to find a precise balance between the amount of stability and mobility. It is also shown that, in the search for this balance, the role of sensory-motor control is much more important than the role of strength or endurance of the trunk muscles. Future research should further reveal the complex biomechanics and muscle activations, thereby allowing more detailed evaluation methods and more specific training or rehabilitation protocols.

No positive relationship has been found in the literature between core stability and physical performance. More research in this area is needed with adequate training programmes and sufficiently sensitive measurement protocols. With respect to the association between core stability and injury, various studies have found that a decrease in core stability is related to a higher risk of sustaining a knee injury or low back pain. Furthermore, it is found that deficient neuromuscular core control predisposes athletes to low back and lower extremity injuries. In addition, studies conducted to correlate hip muscle characteristics with injury also found that decreased strength, poor endurance and delayed firing are associated with lower extremity and low back injuries. Based on these findings, it would be interesting for future research to look at the relationship between the activation speed of the trunk muscles and the speed of activation of the hip musculature. Furthermore, it is recommended to follow athletes through multiple sport seasons, by making use of prospective longitudinal studies, to further investigate the relationship between core stability and injury risk.

Several studies demonstrated that delayed firing of the trunk muscles and neuromuscular imbalance are associated with low back pain. In addition, decreased balance performance was also found to be related to the occurrence of low back pain.

Only one study has been found in which the relationship between balance performance and trunk muscle response times is investigated. A significant correlation was found between poor balance performance in a sitting balance task and delayed firing of the trunk muscles during sudden perturbation and it was suggested that both phenomena were being caused by proprioceptive deficits. Further research is needed to lay a stronger foundation for this relationship. In addition, investigation is required to look for the cause of delayed muscle responses and to see whether decreased muscle response times actually result in a reduced risk of injury.

With respect to the training of core stability, it is shown that stressing the propriocepsis during training activities leads to increased demands on trunk muscles, thereby improving core stability and balance, which are important aspects in sport. In this respect, creating unstable surfaces, for example through the use of a Swiss ball, is a clever way to stress the trunk muscles. In addition, in various articles the importance of functional training is emphasized. Further investigation is warranted to validate the use of Swiss balls in physical training programmes and future research is required to develop specific, functional training protocols in various sport domains and in the field of rehabilitation.

In section 5, several tests were discussed in which balance, trunk muscle activation characteristics and proprioception have been measured. One study even tried to quantify core stability by calculating an index of spine stability. On the basis of findings discussed in section 3, it can be stated that sitting balance performance and trunk muscle response times may be good indicators of core stability, although much more research in this domain is needed to further ground the various relationships. Simple quantitative test procedures have to be designed and evaluated that are of clinical use and that reflect the sensory-motor control aspects of the neuromuscular system surrounding the lumbar spine. Taking practical issues into consideration, it can be noticed that the use of EMG measurements to investigate trunk muscle reaction times is quite demanding and expensive. It would be interesting to quantify core stability using a balance task, for example by measuring centre of pressure-displacements or by making use of accelerometry. Future research is required to develop such a task and to adjust it to the specific demands of various target groups, such as patients or athletes. The development of sensitive measures can lead to the identification of neuromuscular risk factors that predispose athletes to low back and lower extremity injuries. On the basis of such evaluations, interventions can be developed to modify the risk factors, thereby decreasing the risk of injury.

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3. Core Muscle Response Times And Postural Reactions in Soccer Players and Nonplayers

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Abstract

Decreased core stability has been suggested to be associated with a higher occurrence of lower extremity injuries and low back pain. In a physical contact sport like soccer, direction-specific muscle reflex responses are crucial in maintaining core stability. Delayed core muscle response times repeatedly have been reported in patients with low back pain, but no study has compared core muscle reflex latencies and postural control between soccer players and less active nonplayers. **Purpose:** The goal of this study was to investigate whether soccer players will exhibit shorter average core muscle reflex latencies along with less postural sway in response to a sudden trunk perturbation compared with nonplayers. A second goal was to see whether postural control measures are a valid, more practical alternative for the use of surface EMG in measuring reflexive core neuromuscular control. **Methods:** Sudden trunk loading in the frontal and sagittal plane was used in 10 high-level amateur soccer players and 11 less active nonplayers to study core muscle reflex latencies, using surface EMG of six major trunk muscles. Simultaneously, kinematic response data of a balance seat were obtained using gyroscopes measuring seat angular velocity. **Results:** Soccer players demonstrated shorter reflex latencies compared with nonplayers for the rectus abdominis, erector spinae, and externus obliquus muscles in response to sagittal plane perturbations. These shorter reflex latencies went along with greater seat movement in response to sudden trunk loading, with moderate correlations between the two measures. **Conclusions:** The results showing shorter reflex latencies and greater balancing movements for soccer players add to the debate whether more postural sway is an appropriate indicator of having less neuromuscular control.

Key Words

Core Stability, Trunk Muscular Reflexes, Postural Sway, Sudden Trunk Loading

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Introduction

Core stability is an important concept in clinical rehabilitation and in the training of competitive athletes. The core serves as the center of the functional kinetic chain, and as such, it is seen as the foundation of all limb movement. Several studies have found that deficient core neuromuscular control predisposes athletes to low back and lower extremity injuries.[6,10,23,33,34] The term core stability, as used in the present study, describes the ability of the neuromusculoskeletal system to maintain or resume an upright position of the trunk in the presence of disturbances. Within this definition, stabilizing the core is a dynamic process of maintaining balance. Core stability is maintained primarily by well-coordinated neuromuscular control. Within an ever-changing environment, like during a soccer game, rapid postural responses to both internal and external perturbations are required to maintain balance.[7] The body is continuously stabilized ahead of movement execution (feed-forward) as well as to correct for execution errors and external perturbations (feedback).[1] Integrated proprioceptive input at all levels of the nervous system functions to trigger postural response synergies both in anticipation and in response to sudden changes in the motor program or the environment. This way, proprioception contributes to complex neuromuscular processes that underlie postural control and balance, with an important role for timely reflexive neuromuscular responses in allowing the body to remain stable.[1,7]

A reflex is defined as a change in muscle activation in immediate response to an external perturbation, thereby leading to a change in force. It seems that, under most circumstances, muscle reflex responses correct for insufficient initial stability to constrain trunk motion within a safe boundary.[5,17] Although trunk muscle reflexes aid in stability and have certain advantages (reduced energy expenditure and decreased cumulative tissue loading) compared with intrinsic stiffness alone, reflex delay may adversely affect stability of the core.[9,11] Reflex delay represents the time from a perturbation to the onset of reflex activation.[8] Failure to recruit an appropriate and timely activation response will risk instability injury.[11] This is supported by several studies that have documented decreased trunk proprioception, delayed muscle reflex latencies to perturbation, and decreased postural control in low back pain patients.[6,10,23]

In clinical rehabilitation and sports, various attempts have been undertaken to define core stability and to improve dynamic lumbar stabilization. There is a need for sports physicians to use a simple quantitative test procedure to measure core stability. Because adequate sensory-motor control is very important in providing core stability, such a test should focus on measuring performance during a task in which the core neuromuscular system is stressed. This could be useful in screening athletes to see whether they are at a higher risk of sustaining an injury or whether they maintain a non-optimal balance between stability and mobility.[2] Measures of postural sway during unstable seated balance have been used as measures of trunk postural control[5] and have been related to spinal stability.[26] Until now, only one study[23] has examined the relationship between seated balance performance and core muscle properties. The most important outcome of this study was the finding that, in the absence of visual feedback, poor balance performance correlated significantly with longer core muscle onset times in response to sudden force release. The authors noted that this suggests the existence of a common pathology underlying both phenomena.[23]

Hitherto, no study has compared core muscle reflex latencies and postural control between healthy inactive and active subjects. Therefore, a first aim of the present study was to investigate whether subjects who compete at a high level in indoor and outdoor soccer have a better reflexive core neuromuscular control than less active non-soccer players who do not participate in any organized sport. Because soccer players encounter more situations in which the core musculature is stressed to a high extent and thus probably experience a higher degree of neural adaptations than nonplayers, it was hypothesized that the soccer players will show shorter core muscle reflex delays along with less postural sway in response to a sudden trunk perturbation, thanks to a better-trained and -developed proprioception and thus a higher sensory acuity. In elite and subelite soccer, players are involved in a high number of actions that cause sudden loading of the upper body, like shoulder tackles, turns, stops, headings, and dribbles.[3,16] Pedersen et al.[20] have found that untrained women playing recreational soccer perform three of these activities each min. They have found that 1 h of recreational soccer training twice a week can significantly improve the reflex response to sudden unexpected trunk loading compared with running training or a control group, indicating that soccer training can improve the reaction and coordination in the trunk.[20]

Taking practical issues into consideration, it can be noticed that the use of surface EMG to investigate core muscle reflex latencies is quite demanding and expensive. Therefore, a second aim of the present study was to investigate whether postural control measures are a valid alternative for the use of EMG in measuring reflexive core neuromuscular control. Whereas Radebold et al.[23] used two different tests (a quick force release test and an unstable sitting test) to correlate core muscle response times and balance performance, the present study investigates this relationship using only one test (unstable sitting test with sudden perturbations) in which both measures are being obtained at the same time. On the basis of findings by Reeves et al.,[24] it was hypothesized that, in subjects with a longer reflex delay, a larger amount of postural sway is required to elicit a reflex response because of less sensory acuity.

Materials and Methods

A total of 10 soccer-playing students, participating at a high amateur level in indoor and outdoor soccer, and 11 nonplaying students, who did not participate in any organized sport, volunteered for this study and signed an informed consent form. Subjects also completed a questionnaire containing personal data (Table 1). All subjects were free of chronic low back pain, and no subject reported having neurological or musculoskeletal problems. The training of the soccer players consisted of regular, soccer-specific exercises, without particular attention to the training of the core musculature. The study was approved by the local ethics committee of the Medical Faculty of the University Medical Center Groningen, University of Groningen.

Table 1. Subject data

	Non-soccer	Soccer
n	11	10
Age, yr	21.7 (2.0)	23.7 (0.9)
Weight, kg	74.6 (9.0)	74.3 (6.1)
Height, m	1.88 (0.04)	1.83 (0.07)
Perturbation height,[a] m	0.53 (0.04)	0.52 (0.03)
Sport, h·wk^{-1}	1.3 (0.9)[b]	5.6 (1.2)

Values are mean (SD)

[a] Height from table surface to perturbation rods

[b] Nonplayers mainly participated in sport activities like running, swimming, tennis, and volleyball

Subjects were placed on a seat equipped with a foot support to prevent any leg movement (Figure 1). A sitting posture was chosen to investigate the postural control of the lumbar spine in isolation from the control of the lower limbs. A polyester hemisphere with a radius of curvature of 36 cm was attached to the bottom of the seat (Figure 2), which was placed on a table. A safety railing in front of the subjects provided security in case of loss of balance. Subjects were instructed to maintain balance while sitting upright with the feet positioned shoulder-width apart on the support, hands resting on the thighs, and eyes open. The subjects sat with their hips flexed at 90° to place the seat in a horizontally balanced position. Sudden perturbations in the frontal and sagittal plane were presented to the subjects by making use of a pneumatic perturbation device. The perturbation device was connected by a jointed rod to a girdle that was placed around the subjects' upper trunk at approximately the 9th/10th thoracic level (Figure 3).

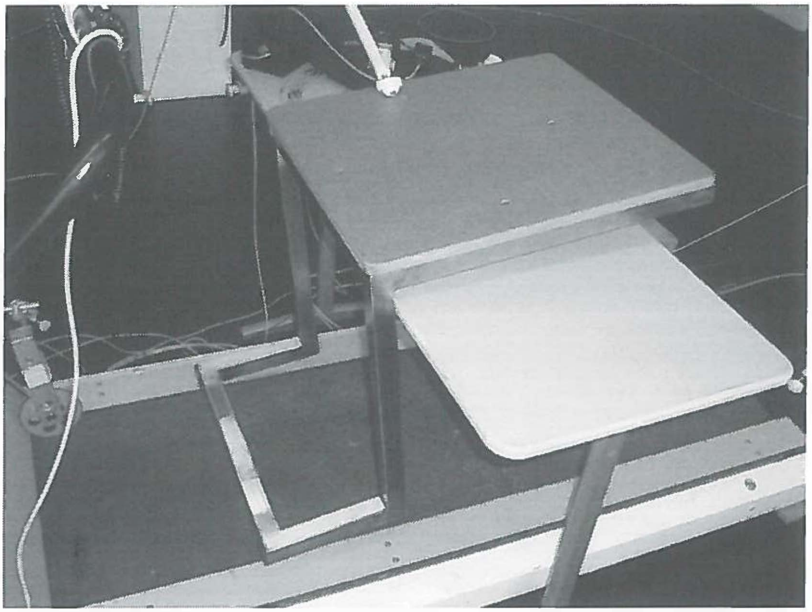

Figure 1. Balance seat equipped with foot support placed on the edge of a table.

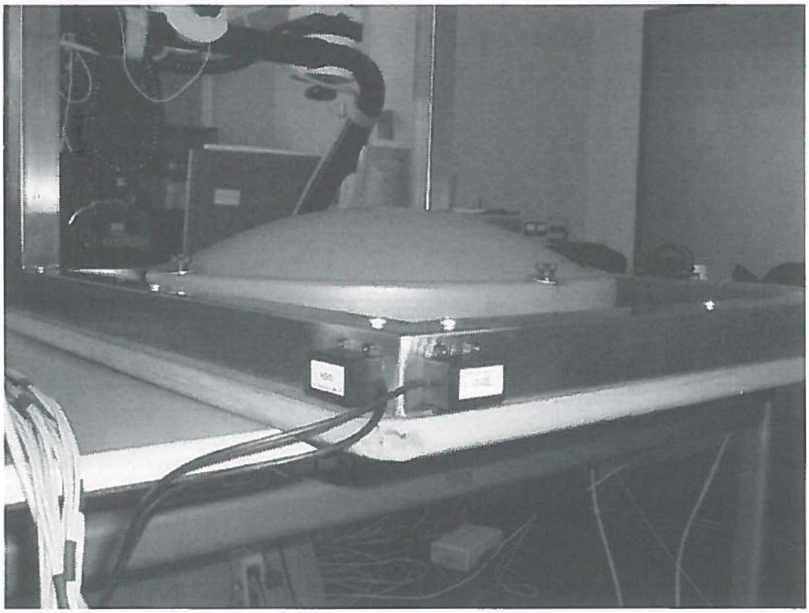

Figure 2. Polyester hemisphere (radius of curvature = 36 cm) and gyroscopes attached to the bottom and the sides of the balance seat, respectively.

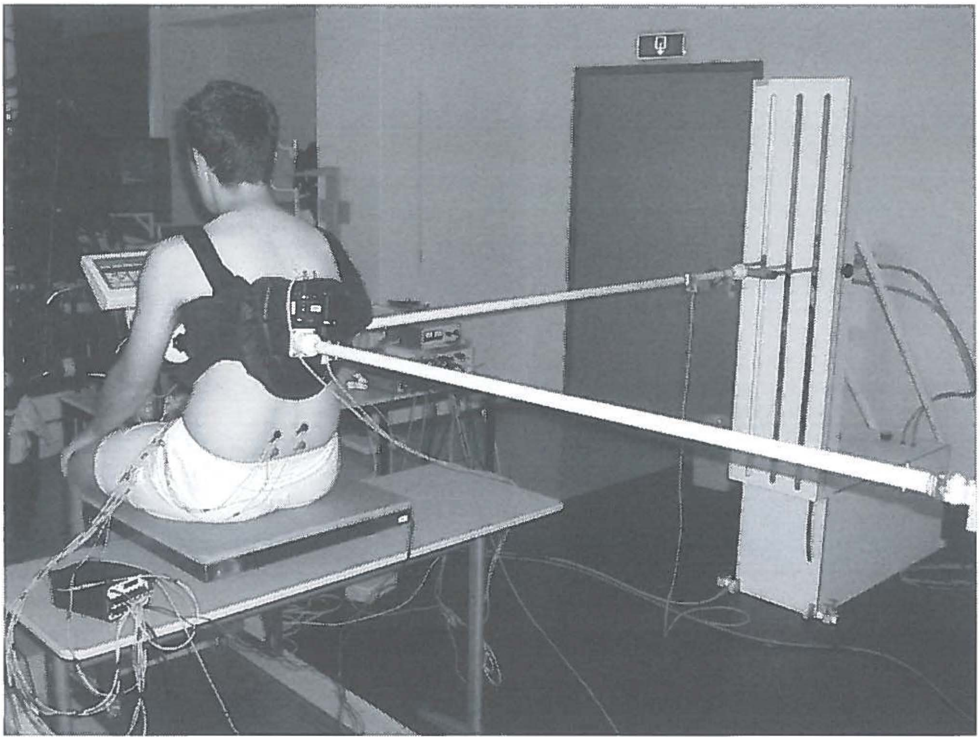

Figure 3. Subject on the balance seat with rods of the perturbation device attached to the girdle that was placed around the upper trunk.

The balance of the subjects was disturbed through either pushing or pulling the upper trunk, both for/backward *(x* direction) and left/rightward *(z* direction). A total of 60 short force impulses, with a duration of 100 ms to peak force level, were presented to each subject in both planes in a random order: 40 perturbations in the sagittal plane (20 forward and 20 backward) and 20 perturbations in the frontal plane (10 leftward and 10 rightward). Peak force levels of half of the perturbations in the sagittal plane were 123.1 + 10.3 N (mean + SD). The other half of the sagittal perturbations and all perturbations in the frontal plane had a magnitude of 80.9 + 8.3 N. Between perturbations, there was a random time of 5-8 s in which subjects were able to get ready for the next perturbation. Before the data collection trial, a practice trial was presented to get the subjects accustomed to the task and to minimize any learning effects. Subjects were instructed to correct for the perturbations by only making corrective trunk movements. The instruction was to relax the core muscles in advance of the perturbations to minimize the effect of cocontraction. After a perturbation, subjects had to react by moving back to equilibrium as soon as possible.

Surface EMG signals were recorded from six major trunk muscles. After site preparation, the electrodes were placed with a center-to-center spacing of 2 cm over the following muscles on each site of the body: lumbar erector spinae (ES; 4 cm lateral to the L3 spinous process), rectus abdominis (RA; 3 cm lateral to the umbilicus), and external oblique (EO; 10-15 cm lateral to the umbilicus with an orientation of 45° to vertical). A reference electrode was placed at the sacrum. All EMG signals were preamplified and A/D-converted (22 bits) by a 32-channel Porti ambulatory recording system at a sample rate of 800 Hz. For determining EMG-based muscle reaction times, 800 Hz was considered sufficient. Lariviere et al.[15] even found that 512 Hz should practically never lead to invalid EMG parameter estimations, although it has to be noted that they did not examine muscle reflex latencies. After recording, the EMG signals were filtered with a high-pass Butterworth filter (fourth-order 20-Hz cutoff frequency) to remove electrode artifacts. ECG artifacts were removed using a method described by Hof.[12]

Movements of the balance seat were measured using two gyroscopes (Murata, Kyoto, Japan; sensitivity = 0.67 $mV \cdot {}^{\circ -1} \cdot s^{-1}$, range $+90^{\circ} \cdot s^{-1}$), measuring angular velocities in the pitch and roll planes (Figure 2). Together with the EMG signals, the force signals of the perturbations and the gyroscope data were preamplified and A/D-converted at a sample rate of 800 Hz by Porti.

Reflex latencies of the muscles acting antagonistic to the perturbation moment were determined. Muscle reaction time (RT) was defined as the time delay from onset of the impact force to EMG onset (Figure 4). EMG onset was detected using an approximated generalized likelihood ratio algorithm developed by Staude and Wolf.[29] For all possible values of RT during an interval of 1 s, the ratio "(variance after RT) / (variance before RT)" was determined. The value of RT at which the logarithm of this ratio was maximal was selected as the most probable onset time. Because the assumptions that reflex responses could not occur earlier than 30 ms after the onset of perturbation and that responses longer than 150 ms could be voluntary and no longer reflexive were made, only reflex latencies within this interval were considered in the analysis. For the sagittal plane perturbations, for which the muscles acting antagonistic to the perturbation were analyzed bilaterally, the shortest latency of the two (left and right) was used in the analysis. The detection of EMG onset sometimes required manual correction because of the remaining signal and ECG artifacts.

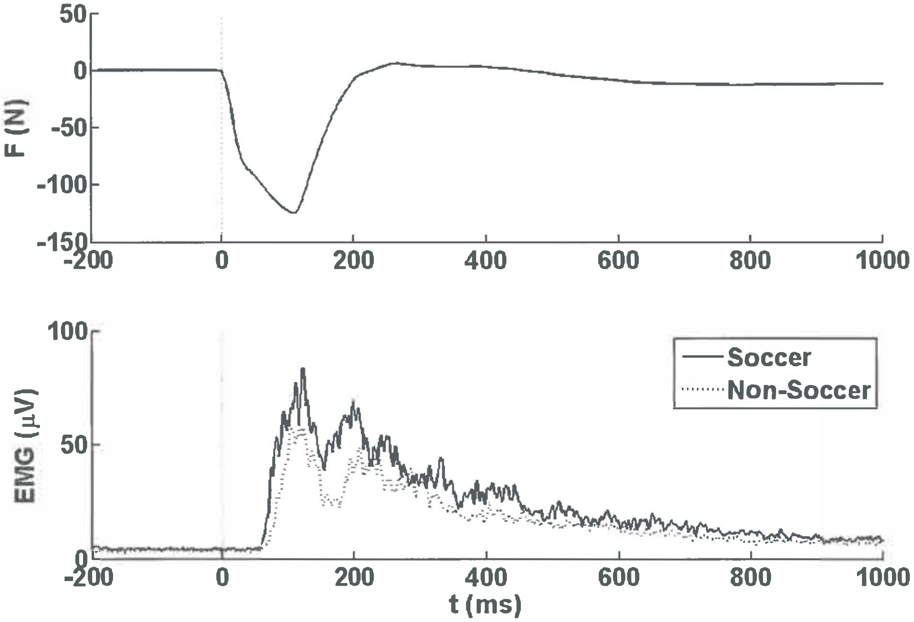

Figure 4. Muscle response to sudden trunk loading. The rectified EMG profile of the EO muscles in response to a large backward pull of both soccer players and nonplayers, averaged for about 100 perturbations. The maximum value for the SEM of the overall averaged EMG profile is 7.0 μV. The trunk force perturbation was applied at time zero (*dotted line*).

From the gyroscope data, root mean square (RMS) values of the seat angular velocity (ω_{RMS}) were determined during a period of 1 s after perturbation onset. Maximum seat angular velocity due to the counteracting reaction of the subject in the direction opposite to the perturbation (ω_{max}) was determined in the pitch and roll planes for perturbations in the sagittal and frontal planes, respectively (Figure 5). Muscle reflex latencies and the mechanical measures mentioned above were all obtained using Matlab software (Natick, MA).

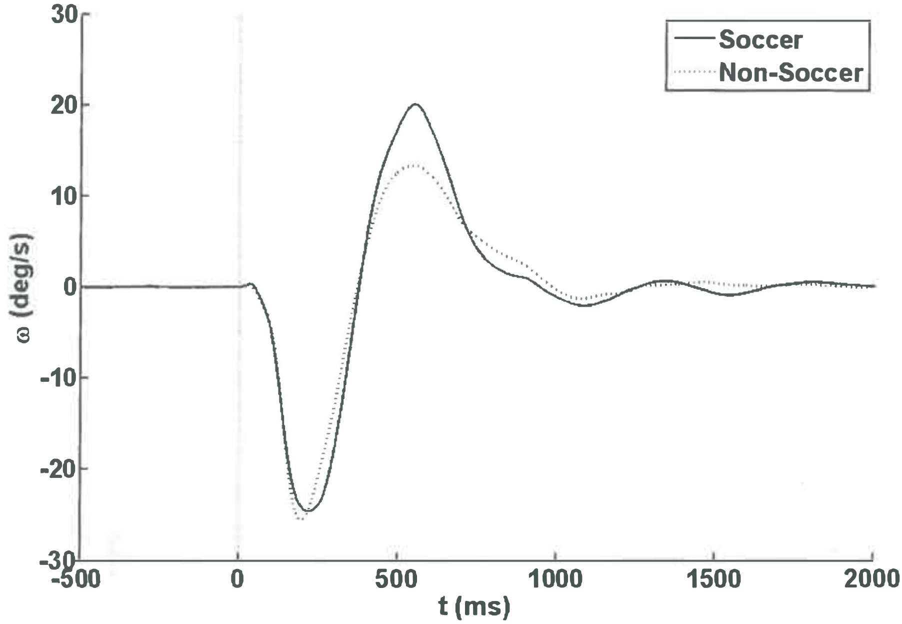

Figure 5. Profile of the seat angular velocity in the pitch plane in response to sudden small backward pulls for both soccer players and nonplayers, averaged for about 100 perturbations. The maximum value for the SEM of the overall averaged angular velocity profile is 1.0 $°\cdot s^{-1}$. Notice the higher ω_{max} value for the soccer players (*second peak*). These responses are typical for all kind of perturbations. The trunk force perturbation was applied at time zero (*dotted line*).

Because of their nonnormal distribution, nonparametric tests were performed to compare the outcomes. To test the hypothesis that soccer players show shorter reflex delays along with less postural sway compared with nonplayers, differences in core muscle reflex latencies and seat kinematic data (ω_{max} and ω_{RMS}) between the two groups were tested with a Mann-Whitney *U* test, applying the test for each type (combination of direction and magnitude) of perturbation separately. To investigate the relationship between the core muscle reaction times and the mechanical measures of seat displacement, both measures were averaged for each subject, and subsequently, correlations between them were calculated using Spearman ρ correlation coefficient, again for each kind of perturbation separately. Correlations were calculated for all subjects together because correlations computed for soccer players and nonplayers separately did not result in any improved outcomes. All statistical analyses were performed using SPSS software (Chicago, IL), with $P < 0.05$ indicating statistical significance.

Results

Table 2. Core muscle reflex latencies and kinematic data of the balance seat in response to different kind of perturbations compared between soccer players and nonplayers

		muscle	rt,[c] ms	ω_{max}, $°\cdot s^{-1}$	ω_{RMS}, $°\cdot s^{-1}$
x-forward (80.9 N)[a]	**Soccer players (68)[b]**	**ES**	91 (17)	26.2 (15.2)	13.1 (5.3)
	Nonplayers (74)	**ES**	109 (24)*	14.8 (9.7)*	8.7(4.2)*
x-forward (123.1 N)	**Soccer players (66)**	**ES**	88 (18)	36.2 (19.6)	18.2 (6.3)
	Nonplayers (84)	**ES**	105 (27)*	21.6 (12.5)*	13.3 (4.9)*
x-backward (80.9 N)	**Soccer players (77)**	**RA**	87 (16)	31.0 (14.9)	16.1 (4.6)
	Nonplayers (94)	**RA**	94 (15)*	20.2 (8.6)*	12.8 (4.5)*
x-backward (80.9 N)	**Soccer players (89)**	**EO**	78 (12)	30.4 (14.2)	15.5 (4.7)
	Nonplayers (96)	**EO**	85 (12)*	20.2 (8.6)*	12.8 (4.5)*
x-backward (123.1 N)	**Soccer players (92)**	**RA**	87 (19)	32.7 (15.5)	20.6 (5.6)
	Nonplayers (97)	**RA**	91 (15)*	23.6 (8.1)*	17.8 (4.9)*
x-backward (123.1 N)	**Soccer players (98)**	**EO**	76 (11)	32.2 (15.8)	20.3 (5.6)
	Nonplayers (101)	**EO**	82 (10)*	23.8 (8.4)*	17.7 (4.9)*
z-leftward (80.9 N)	**Soccer players (58)**	**EO right**	102 (23)	17.0 (10.6)	9.2 (4.1)
	Nonplayers (79)	**EO right**	96 (21)	10.4 (5.8)*	6.6 (2.3)*
z-rightward (80.9 N)	**Soccer players (51)**	**EO left**	106 (19)	15.5 (8.2)	7.9 (3.4)
	Nonplayers (84)	**EO left**	99 (12)	10.3 (6.0)*	6.2 (2.5)*

Values are mean (SD)

[a] Direction of perturbation (mean peak force level)

[b] Subject category (number of perturbations investigated)

[c] Muscle reaction time in milliseconds

* Statistically significant different from soccer players ($P < 0.05$)

Results of the Mann-Whitney *U* test showed that, for each type of perturbation in the sagittal plane, muscle reaction times of the muscles acting antagonistic to the perturbation moment (ES for forward perturbations and RA and EO for backward perturbations) were significantly smaller for the soccer players compared with those for the nonplayers ($P < 0.01$). With respect to the sideward perturbations, muscle reaction times of the EO muscles were smaller for the nonplayers nearing statistical significance ($P = 0.056$; Table 2). Values for ω_{max} and ω_{RMS} were significantly smaller for the nonplayers for all types of perturbation *(*$P < 0.001$; Table 2). This indicates a lower peak angular velocity in moving the balance seat back to equilibrium and, consequently, a lower amount of seat movement in response to the perturbations, which is visualized in Figure 5. With respect to the relationship between core muscle reflex latencies and seat kinematic data, for the sagittal plane perturbations, negative correlations were found, whereas for the frontal plane perturbations, core muscle reflex latencies correlated positively with ω_{max} and ω_{RMS} (Table 3). For the large forward perturbations, reaction times of the ES muscles correlated significantly with ω_{RMS} values at the 0.05 level, with a correlation magnitude of -0.583. For the other types of perturbation, correlations were weak and inconsistent (Table 3).

Table 3. Spearman ρ correlations between core muscle reflex latencies and kinematic data of the balance seat in response to different kind of perturbations

	muscle		rt, ms[b]
x-forward (80.9 N)[a]	ES	ω_{max}, °·s^{-1}	-0.346 (0.135)
		ω_{RMS}, °·s^{-1}	-0.427 (0.060)
x-forward (123.1 N)	ES	ω_{max}, °·s^{-1}	-0.359 (0.120)
		ω_{RMS}, °·s^{-1}	-0.583 (0.007)*
x-backward (80.9 N)	RA	ω_{max}, °·s^{-1}	-0.357 (0.112)
		ω_{RMS}, °·s^{-1}	-0.281 (0.218)
x-backward (80.9 N)	EO	ω_{max}, °·s^{-1}	-0.095 (0.681)
		ω_{RMS}, °·s^{-1}	-0.001 (0.996)
x-backward (123.1 N)	RA	ω_{max}, °·s^{-1}	-0.229 (0.319)
		ω_{RMS}, °·s^{-1}	-0.191 (0.407)
x-backward (123.1 N)	EO	ω_{max}, °·s^{-1}	-0.016 (0.947)
		ω_{RMS}, °·s^{-1}	-0.140 (0.544)
z-leftward (80.9 N)	EO right	ω_{max}, °·s^{-1}	0.016 (0.947)
		ω_{RMS}, °·s^{-1}	0.155 (0.504)
z-rightward (80.9 N)	EO left	ω_{max}, °·s^{-1}	0.316 (0.163)
		ω_{RMS}, °·s^{-1}	0.355 (0.115)

Values are correlation (*P*-value)

[a] Direction of perturbation (mean peak force level)

[b] Muscle reaction time in milliseconds

* Statistically significant correlation ($P < 0.05$)

Discussion

The first aim of this study was to investigate whether subjects who regularly participate in soccer will show shorter core muscle reflex delays along with less postural sway in response to a sudden trunk perturbation compared with less active nonplayers. With respect to the muscle reaction times, the results showed significant shorter reflex delays for the ES, RA, and EO muscles in soccer players for the sagittal plane perturbations (Table 2; RT), but this difference was not reflected in less seat movement (expressed as smaller values for ω_{RMS}) in response to the perturbations. Although no significant differences were found for the frontal plane perturbations, the shorter muscle reaction times of the EO muscles for the nonplayers might still be functionally significant.

The second aim of the present study was to investigate whether postural control measures are a valid alternative for the use of EMG in measuring reflexive core neuromuscular control. Our hypothesis was that longer reflex delays would be associated with greater seat movement. The results showed the opposite with respect to the forward and backward perturbations; although soccer players showed smaller core muscle reflex delays compared with nonplayers for perturbations in the sagittal plane, seat movement in response to these perturbations was found to be larger in soccer players (Table 2; ω_{RMS}). Although a significant negative correlation was found between ES muscle reaction times and the amount of seat movement for the large forward perturbations, the overall magnitude of the correlations found ranged between weak and moderate, without showing any other significant value. Furthermore, for the frontal plane perturbations, positive correlations were shown between core muscle reflex latencies and seat kinematic data.

These findings indicate that there was no consistency between the various correlations, indicating no clear association between the two measures. The first response to the perturbations occurred with reflex latencies corresponding to long-latency stretch reflexes or preprogrammed muscle responses.[19] The weak relationship between core muscle onset times and seat kinematic data might be explained by the core muscle onset giving an indication of the speed of response onset, whereas the mechanical measures are telling more about the quality of the responses. Skotte et al.[28] conducted a sudden trunk loading experiment in which they found a shortened trunk stopping time, without finding shortened trunk muscle reaction times. The mechanical improvement was due to a more efficient preprogrammed response, indicating that only looking at EMG reaction times may be insufficient to detect improvements in the execution of preprogrammed reactions.[19] In the present study, soccer players might have relied more on better-developed feed-forward processes for their responses, with concurrent proprioceptive feedback being less important. This stronger reliance on feed-forward processes during the preprogrammed responses may be related to a higher response velocity.[1] In this respect, an interesting finding of the present study is the soccer players moving back to equilibrium with a higher maximum seat angular velocity compared with the nonplayers, for all types of perturbation (Table 2; ω_{max}). At present, there is discussion about whether more postural sway during a balance task is always associated with poorer balance performance and less stability. Assuming that shorter muscle reflex latencies are a reliable indicator of increased dynamic stability, the present study illustrates that more sway is not necessarily associated with less stability. This is in accordance with a recently published study by Van Dieën et al.[31], who found that lower sway velocity during a sitting balance task is associated with less stability (indicated by a loss of balance).

Although various studies have shown delayed core muscle reflex responses in patients with low back pain,[4,6,22,23] no previous study has shown that core muscle reaction times are shorter in soccer players compared with less active nonplayers. The finding that reflex delays of soccer players were shorter for perturbations in the sagittal plane, but not in the frontal plane, may reflect the lumbar spine's natural propensity for sagittal plane movement.[18] Muscles acting in the sagittal plane encounter a greater challenge in providing core stability, whereas frontal plane stability is more controlled by passive tissues. Sideward adjustments may depend relatively more on other interacting feedback systems in achieving postural control,[27] as a result of which no differences were found in neuromuscular control between soccer players and nonplayers with respect to the sideward perturbations.

Various studies have demonstrated that core muscle coactivation is associated with reduced trunk displacement,[13,14,30] although the outcomes with respect to the effects of preactivation on trunk muscle reflex latencies are not consistent.[14,24,30] On the basis of these findings, a possible explanation for the smaller amount of seat movement in nonplayers might be increased core muscle cocontraction, although soccer players rely on a more automatized and more adaptive form of postural control with stronger reflexes, which is more efficient with respect to external perturbations.[32] In both groups, the preactivation level of the core muscles was around zero, indicating no cocontraction in advance of the perturbations.

A possible confounder that needs attention is the anthropometric data of the subjects. Cholewicki et al.[5] found a correlation between some balance performance measures and the body weight and torso length of the subjects: the task difficulty was found to be greater for heavier individuals with long upper bodies. The present study did not take into account this possible confounding effect, but when looking at the anthropometric data (Table 1), soccer players and nonplayers on average showed the same weight and torso length. Besides, the correlation found by Cholewicki et al.[5] was not confirmed by Preuss et al.[21]

Because in the present study only weak correlations were found between reflex latencies and mechanical measures of the balance seat, it would be interesting to offer subjects a similar perturbation test during which kinematic data of the upper trunk—instead of the seat—are obtained and compared with the core muscle reflex latencies. A clearer association between these two measures is to be expected because of the more direct relationship between core muscle reflexes and trunk movement compared with balance seat movement. On the basis of model simulations, Reeves et al.[25] showed that longer reflex delays produce more balance instability, increased trunk displacement, and greater trunk moments.

In conclusion, the hypothesis that soccer players show shorter muscle reflex latencies than nonplayers was confirmed by the present study for the ES, RA, and EO muscles in response to sagittal plane perturbations. EO muscle reaction times in response to frontal plane perturbations were non-significantly shorter for the nonplayers, which still might be functionally significant. Although the seat kinematic data obtained in the present study give some interesting information about the postural reactions of the subjects in response to a perturbation, it has to be concluded that these postural sway measures are not a valid alternative for the core muscle reflex latencies, measured via EMG. Therefore, further analyses using refined measurement methods are necessary to get more insight into the relationship between core muscle reflex latencies and kinematic data of the balance seat and trunk. The results of this study may aid in the process of developing a practical measurement method that gives an indication of the reflexive core neuromuscular control, which might eventually be implemented in the fields of rehabilitation and sports.

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4. Three Clinical Tests Measuring Core and Whole-Body Stability: *Their Validity, Reliability and Mutual Coherence*

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Abstract

To investigate whether the injury-preventive and performance-enhancing effect of specific interventions is thanks to improvements in the capacity to stabilize the body's core, reliable measurements have to be used to assess neuromuscular control of the core muscles. **Purpose:** The goal of this study was to introduce a graduated sitting balance test and a seated perturbation test as valid measures of core stability and robustness, respectively. Furthermore, test-retest reliability of both tests and of an adapted version of a previously developed graduated narrow ridge test was investigated, together with the relationships between the different test results. **Methods:** Thirty healthy university students performed the three tests two times with a period of one week in between. Intraclass correlation coefficient (ICC), standard error of measurement (SEM) and minimal detectable change (MDC) were calculated to indicate reliability and responsiveness of the test results and correlations were calculated to relate the different test results to each other. **Results:** A systematic bias was found for the balance scores obtained with the graduated narrow ridge test and the graduated sitting balance test and for some measures obtained with the seated perturbation test, indicating a learning effect. ICC values of all test results varied between 0.55 and 0.94. **Conclusions:** Test-retest reliability of the three tests investigated was moderate to substantial, with some measures showing almost perfect reliability. Future research should focus on refining these measurement methods to eventually use them in assessing the effect of neuromuscular interventions on improving core and whole-body stability.

Key Words

Core Stability, Postural Balance, Neuromuscular Control

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Introduction

In the world of sports rehabilitation and athletic training, the focus is more and more on the concept of core stability. According to Borghuis et al.,[4] the core can be seen as the lumbopelvic complex with all its surrounding tissues, like muscles, tendons and ligaments. On the basis of Zazulak et al.,[41] they presented an operational definition of the core stability concept, defining it as the ability of the neuromusculoskeletal system to maintain or resume an upright position of the trunk in labile situations or in the presence of disturbances. In this way, stabilizing the body's core can be seen as a dynamic process of maintaining balance, regulated by well-coordinated sensory-motor control of all the trunk muscles.[4] In case of internal or external balance perturbations, the neuromuscular system uses anticipatory postural adjustments (APA's) and muscle reflex responses to maintain core stability.[40] When playing sports, quick postural reflexes might often mean the difference between success and failure.

The question remains how to measure and quantify core stability. Consistent terminology should lead to the development of clinical tests giving reliable core stability measures. Such measures are required to investigate the effectiveness of certain sports performance and injury prevention or rehabilitation programs in improving core stability.[32] Measurement techniques can be considered as either clinical or instrumented.[31] Instrumented measures are obtained using sophisticated equipment, like electromyography (EMG) and support surface sensors (force platforms).[5,31,40] At present, posturography (assessing postural coordination by monitoring centre of pressure (CoP) movements of the body support area using a force platform) is becoming increasingly important, both in the clinic and for research purposes.[33] Postural sway is measured either in a static position or in response to a volitional or applied postural perturbation.[26] Trunk postural control is quantified using measures of seated postural sway during unstable seated balance, thereby isolating trunk muscle control in postural stability.[6,28] However, in addition to the disadvantages in terms of costs and time spent, there is continuous debate about optimal selection of discriminative sway parameters.[27] It is commonly assumed that increased variability indicates greater instability.[9] Though, results in this respect are inconsistent.[8,25] Some studies even indicate that variability plays a facilitating role in adaptive postural control, allowing for the exploration of stability boundaries.[22,30] Sensorimotor control is about controlling this variability.[37]

In contrast to these instrumented measures, clinical tests are available that are inexpensive, portable andless time-consuming. Although some of these tests have acceptable to excellent reliability, there is a problem regarding their construct validity.[40] Some clinical 'core stability tests' only asses the static muscular endurance of several global core muscles.[10,24] Other tests consist of observing and rating the performance on static exercises in which subjects have to keep a neutral spine posture, to assess the control of the local core muscles.[10,11,21] Intra- and interobserver reliability of these ratings is found to be insufficient.[39] Besides, the question should be raised as to whether performance on these static tests actually tells us something about core stability in more complex dynamic tasks, keeping in mind that stabilizing the core is a dynamic process of maintaining balance. Low correlations found between the different clinical tests indicate that they may represent different aspects of core muscle capacity.[13,20]

The purpose of the present study is to present some clinical tests to make the concept measurable in a valid and quantifiable way. Reeves et al.[29] noted that it is a mistake to describe the level of stability of a system, because a system is either stable or not. In this respect, they indicated that it is more appropriate to talk about the robustness of a system.[29] Tanaka et al.[34] introduced the threshold of stability (ToS) as a new tool for evaluating core stability. In their study, subjects had to balance on a wobble chair with adjustable springs underneath the seat.[34] The maximum task difficulty in which stability could be maintained (ToS) was determined by moving the springs closer to the center of the seat. This way, it was investigated at what level of task difficulty balance was lost.[34] A similar approach was used by Curtze et al.[7] in measuring one-leg lateral balance control. They developed a narrow ridge balance test in which subjects had to maintain their balance on ridges of gradually decreasing width (Figure 1A & 1B), quantifying their balance capacity using a simple scoring scheme.[7] On the basis of this test, we developed a comparable task to investigate core stability: a graduated sitting balance test. In this test, subjects are seated on sitting boards with circle segments of varying diameters mounted underneath, so that the seat can roll over a table surface (Figure 1C & 1D). Task difficulty is increased by decreasing the diameter of the circle segments. The strength of all these graduated approaches is that they identify and quantify the transition between stable and unstable behavior.[34]

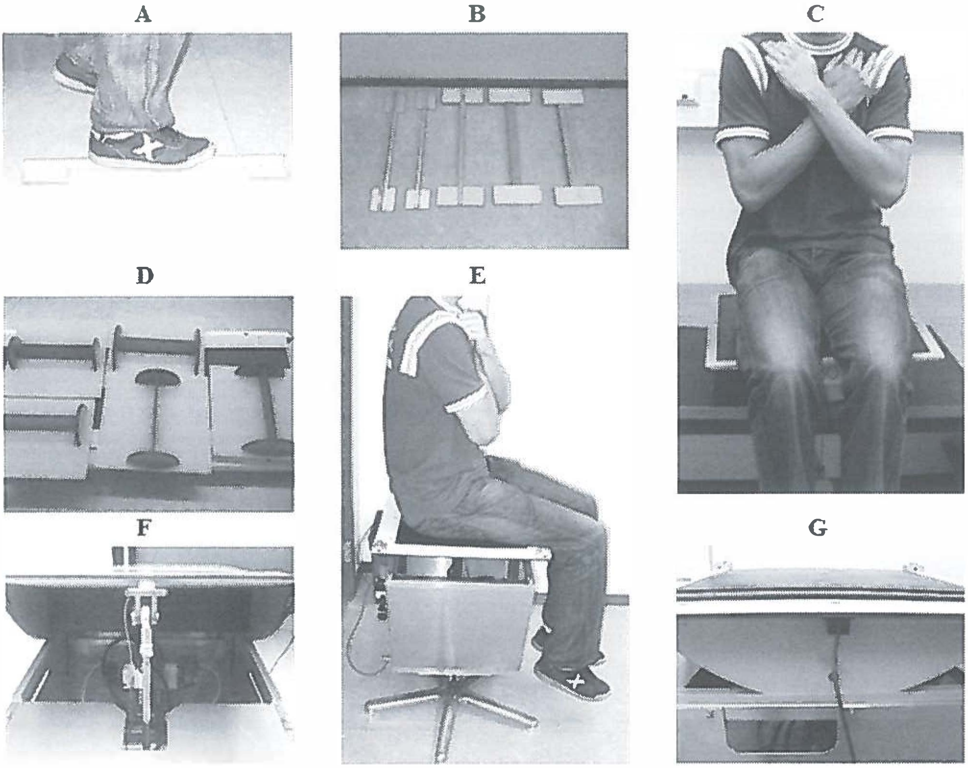

Figure 1. Photos of **(A)** the narrow ridge balance test, **(B)** the ridges used in the narrow ridge balance test, **(C)** the frontal plane graduated sitting balance test, **(D)** a bottom view of the balance boards used in the graduated sitting balance test, **(E)** the frontal plane seated perturbation test, **(F)** the pneumatic cylinder underneath the seat in the seated perturbation test and **(G)** the gyroscope mounted underneath the seat in the seated perturbation test.

Besides the stability of a system, it is also interesting to investigate its performance. Performance reflects the accuracy and speed with which a system responds to a perturbation.[29] Marshall et al.[23] introduced time to stabilization (TTS) as a performance measure to investigate lower limb function. For the purpose of the present study, we used a comparable measure to quantify performance in a task in which core stability is challenged. In this test, subjects are also seated on a sitting board with two circle segments mounted underneath. The bottom of these circle segments is slightly flattened, thereby creating a stable equilibrium position when seated with the sitting board in a horizontal position (Figure 1E). Stable posture is perturbed by a sudden rotation of the sitting board, caused by the activation of a pneumatic cylinder underneath the seat (Figure 1F). In response to this perturbation, subjects have to return to the equilibrium position as quick and accurate as possible by making corrective trunk movements. The time it takes to return to stable equilibrium is used as a measure of task performance.

In addition to introducing this seated perturbation test and the graduated sitting balance test as measures of core robustness and stability, the purpose of the present study is also to investigate the test-retest reliability of both tests and of an adapted version of the narrow ridge balance test as developed by Curtze et al.[7] Baumgarter[3] introduced the difference between relative and absolute reliability, the former indicating the consistency of the rank of subjects in a sample over repeated measurements, while absolute consistency concerns the degree to which subjects' scores vary over repeated trials. The present study will present an indication of both types of reliability for the three tests conducted. In addition, correlations between the results of the different tests will be presented to get some insight into the relationship between performances on the three postural control tests.

Materials and Methods

Participants

Thirty university students (15 male, 15 female) volunteered for this study and signed an informed consent form. Subjects also completed a questionnaire containing personal data (Table 1). All subjects were free of chronic low back pain and no subjects reported having neurological or musculoskeletal problems. The study was approved by the local ethics committee of the Medical Faculty of the University Medical Center Groningen, University of Groningen. To assess the test-retest reliability of the three postural control tests described below, subjects performed the tests two times with a period of one week in between. Tests were performed in a random order.

Table 1. Subject data

Age, yrs	21.3 (2.1)[a]
Weight, kg	71.1 (10.3)
Height, m	1.76 (0.06)
Hours sport[b] per week:	**Number of subjects:**
< 1	4
1 - 4	10
4 - 7	9
> 7	7

[a] Values are mean (standard deviation)

[b] Subjects mainly participated in sport activities like running, soccer, judo, fitness, tennis and athletics

Narrow Ridge Balance Test

In this test, developed by Curtze et al.,[7] subjects were asked to maintain one-leg balance for 20 s on ridges of gradually decreasing width that were oriented in dorsoventral direction (Figure 1A). Five custom-made ridges were used with a height of 25 mm. The widths of the ridges were 60, 40, 20, 10 and 4 mm (Figure 1B). During the execution of this test, subjects wore comfortable indoor shoes or sneakers with a flat sole. The test procedure used in the present study differed slightly from the procedure as developed by Curtze et al.,[7] to adjust the level of task difficulty to the performance level of the subjects tested. During a trial, subjects had to cross their arms in front of their chest and fixate their gaze on a cross on the wall placed about 2 m in front of them at eye level. Subjects failed on a trial when one of their legs touched the ground or when they started to use their arms in maintaining balance. Balance time was manually recorded with an accuracy of 0.1 s using a stopwatch. Before the test began, subjects were offered a 20 s practice trial on the 60 mm ridge, balancing on their non-dominant leg. Subsequently the test started on the 60 mm ridge, testing the balance capacity on the non-dominant leg. When subjects successfully kept their balance for 20 s, they proceeded to the next level. When subjects were not able to maintain balance for 20 s, they started another attempt on the same ridge. Trials on the narrowest ridge were not aborted after 20 s, but balance time was recorded up to a maximum of 120 s. After three trials balancing less than 20 s or after balancing more than 20 s on the narrowest ridge, the test was stopped. Subsequently, the test procedure was repeated on the dominant leg.

Balance times were converted into a maximum and a mean balance score calculated for each leg individually, using an adapted version of a simple scoring scheme as developed by Curtze et al.[7] Subjects earned ¼ point for every 1-5 s they were in balance, so that they could earn up to 1 point on every ridge. Subjects started with a score of 3 points, because in the original test additional wider ridges were used. When subjects were able to maintain balance on the smallest ridge for more than 20 s, they got additional points. For 20-30 s subjects earned a total of 8¼ points, for 30-60 s 8½ points, for 60-90 s 8¾ points and subjects scored 9 points when they balanced for 90-120 s on the smallest ridge. The maximum balance score was determined, based on the best trial per leg. The mean balance score was calculated by averaging the scores of the trials in which subjects could not maintain their balance (Figure 2).

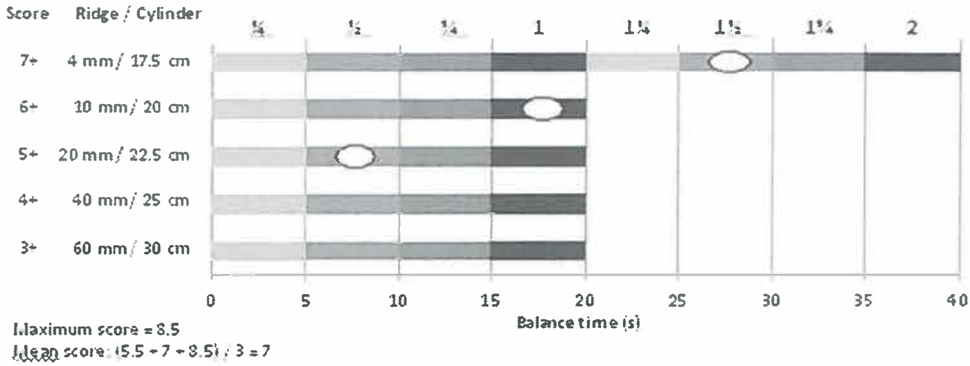

Figure 2. The scoring scheme used in the narrow ridge balance test and graduated sitting balance test, showing an example of determining the maximum and mean balance score.

Graduated Sitting Balance Test

In this test, subjects were asked to maintain seated balance for 20 s on sitting balance boards in either the sagittal (for-/backward) or frontal (left-/rightward) plane (Figure 1C). Five custom-made sitting boards (50 x 50 cm) were used with two circle segments of varying diameter (30, 25, 22.5, 20 and 17.5 cm) mounted underneath (Figure 1D). The boards thus could roll over a table surface, thereby creating unstable seats. The height of the circle segments was 10 cm, such that the seats could rotate about 20° degrees before touching the table. The test procedure and the scoring scheme were the same as the procedure for the narrow ridge balance test described above. During a trial, subjects had to sit upright with knees together in an angle of approximately 90°, their arms crossed in front of their chest and their gaze fixated on a cross on the wall placed about 2 m in front of them at eye level. Subjects failed on a trial when the edge of the seat touched the table or when they started to use their arms in maintaining balance. Before the test began, subjects were offered a 20 s practice trial on the sitting board with 30 cm circle segments, balancing in the sagittal plane. Subsequently the test started on this sitting board, testing the balance capacity in the sagittal plane. When subjects successfully kept their balance for 20 s, they proceeded to the next level. When subjects were not able to maintain balance for 20 s, they started another attempt on the same seat. Trials on the seat with the smallest circle segments were not aborted after 20 s, but balance time was recorded up to a maximum of 2 minutes. After three trials balancing less than 20 s or after balancing more than 20 s on the sitting board with the smallest circle segments, the test was stopped. Subsequently, the test procedure was repeated in the frontal plane. Balance times were again converted into a maximum and a mean balance score calculated for each plane separately, just like described above for the narrow ridge balance test (Figure 2).

Seated Perturbation Test

In this test, subjects were seated on a sitting board with two circle segments (diameter = 50 cm) mounted underneath (Figure 1E). The bottom of these circle segments was slightly flattened (flattening width = 30 mm), thereby creating a stable equilibrium position when seated with the sitting board in a horizontal position. During a trial, subjects had to sit upright with knees together in an angle of approximately 90°, their arms crossed in front of their chest and their gaze fixated on a cross on the wall placed about 2 m in front of them at eye level. When seated in this position, stable posture was perturbed by a sudden rotation of the sitting board, caused by the activation of a pneumatic cylinder underneath (Figure 1F). In response to this perturbation, subjects had to return to the equilibrium position as quick and accurate as possible by making corrective trunk movements. During the first trial, subjects were presented with 30 random perturbations in the sagittal plane (15 forward and 15 backward), of which the first 10 perturbations formed a practice trial to get the subjects accustomed to the task and to minimize any learning effects. The second trial comprised 30 random perturbations in the frontal plane (15 leftward and 15 rightward), the first 10 perturbations again forming a practice trial. There was a random time interval of 5-8 s in between subsequent perturbations. The perturbations consisted of 100 ms force impulses. The pressure of the pneumatic cylinder, and thereby the magnitude of the perturbation moment, was proportional to the weight of the subjects. The force impulses created on average a perturbation moment of 0.7 $Nm \cdot kg^{-1}$ body weight for the back- and leftward perturbations and 0.8 $Nm \cdot kg^{-1}$ body weight for the for- and rightward perturbations.

Angular velocity of the balance seat in response to the perturbations was measured using a gyroscope (Murata; sensitivity 0.67 $mV \cdot {}^{\circ -1} \cdot s^{-1}$, range ± 90 $^{\circ} \cdot s^{-1}$) (Figure 1G). Two other gyroscopes, attached to a girdle that was placed around the subjects' upper trunk at approximately the 5th/6th thoracic level, were used to measure trunk movements in the frontal and sagittal plane. From the seat gyroscope data, TTS was determined as the time it took a subject to sit still in the equilibrium state for at least 0.5 s after perturbation onset. TTS was seen as the primary outcome measure. Besides TTS, several kinematic variables were determined from the gyroscope data (Table 2). When a subject was not in the equilibrium state during perturbation onset or when TTS exceeded 3 s, the corresponding perturbation was not considered in the analysis. For every perturbation direction, only the three perturbations with the smallest TTS were eventually taken into the analysis, to correct for a possible effect of fatigue or lack of concentration. All measurement data were acquired using Labview software and outcome measures were obtained using Matlab.

Table 2. Definitions of the kinematic variables used as secondary outcome measures of the seated perturbation test

Kinematic variable	Definition
ω_{seat} (°/s)	Maximum angular velocity of the seat while returning to equilibrium
ω_{trunk} (°/s)	Maximum angular velocity of the trunk while returning to equilibrium
RMSω_{seat} (°/s)	Root mean square value of the seat angular velocity from perturbation onset to recovery of stable equilibrium
RMSω_{trunk} (°/s)	Root mean square value of the trunk angular velocity from perturbation onset to recovery of stable equilibrium

Data Analysis

Results of Kolmogorov-Smirnov tests indicated that all data were normally distributed, except for the sagittal plane scores in the graduated sitting balance test and the trunk data in response to the for-/backward perturbations in the seated perturbation test. The data were first examined graphically using scatter plots and Bland-Altman plots. To investigate whether there was any systematic bias, paired samples t-tests or Wilcoxon signed ranks tests were conducted. To quantify relative reliability of the three postural control tests, two-way random consistency intraclass correlation coefficients (ICC's) were calculated. Relative reliability of the maximum balance scores was quantified using single measure ICC's, while average measure ICC's were used to quantify relative reliability of the mean balance scores and the seated perturbation test data. With these ICC values, standard error of measurement (SEM) was calculated to give an index of absolute reliability. Subsequently, SEM values were used to estimate minimal detectable change (MDC) at the 95% confidence level, indicating the minimal amount of change that is not due to measurement variation.[14] To see whether there was any relationship between the scores on the different postural control tests, Pearson and Spearman correlation coefficients were calculated between subjects' test scores averaged over test 1 and 2. All statistical analyses were performed using SPSS software with $P < 0.05$ indicating statistical significance.

Results

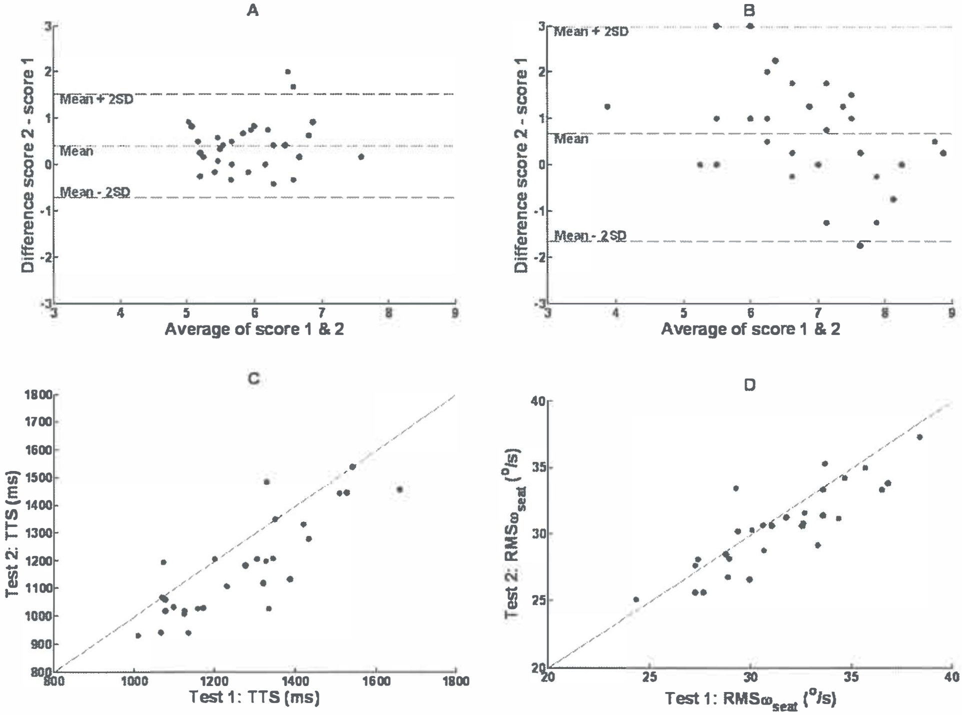

Figure 3. Bland-Altman plots of **(A)** mean standing balance scores for the non-dominant leg and **(B)** maximum sitting balance scores for the frontal plane; scatter plots with lines of equality for **(C)** TTS and **(D)** RMSω$_{seat}$, the data averaged over all four perturbation directions.

Narrow Ridge Balance Test

Figure 3A shows a Bland-Altman plot of the mean standing balance scores determined while testing balance capacity on the non-dominant leg. It can be seen that the average scores of test 1 and 2 ranged between 5 and 8 points for our subject population. This is representative for all maximum and mean standing balance scores obtained on both the dominant and non-dominant leg, with almost all scores lying within this range. Table 3 shows that the maximum and mean balance scores, averaged over all subjects, were significantly higher on test 2 compared to test 1, indicating a systematic bias between the results of the two test sessions. This is also shown in figure 3A, with the mean difference between the two test sessions being positive. The ICC's for these scores were moderate, ranging from 0.66 – 0.81 (Table 3). SEM values ranged between 0.3 and 0.5 points, while MDC values varied between 0.8 and 1.4 points (Table 3). ICC's were larger for the mean balance scores compared to the maximum balance scores, while SEM and MDC values were smaller for the mean scores, indicating greater reliability.

Table 3. Average balance scores (standard deviations) for test 1 & 2; test statistics showing the difference between test 1 & 2; ICC, SEM & MDC values indicating reliability

Test^{a}	Mean (SD) test 1	Mean (SD) test 2	t-value df = 29	ICC (95% CI's)	SEM	MDC
Standing balance						
Max non-dominant	6.2 (0.8)	6.5 (0.9)	-2.76*	0.66 (0.39-0.82)	0.5	1.3
Mean non-dominant	5.7 (0.7)	6.1 (0.7)	-4.05**	0.81 (0.60-0.91)	0.3	0.8
Max dominant	6.4 (0.8)	6.7 (0.9)	-2.12*	0.64 (0.37-0.81)	0.5	1.4
Mean dominant	5.9 (0.6)	6.3 (0.8)	-3.45*	0.76 (0.50-0.89)	0.4	1.0
Sitting balance						
Max sagittal	8.2 (0.7)	8.6 (0.5)	-3.49^{b}**	0.64 (0.36-0.81)	0.4	1.0
Mean sagittal	7.7 (0.9)	8.4 (0.7)	-3.79^{b}**	0.74 (0.46-0.88)	0.4	1.1
Max frontal	6.5 (1.5)	7.2 (1.0)	-3.15*	0.57 (0.27-0.71)	0.8	2.2
Mean frontal	6.2 (1.4)	6.8 (1.0)	-3.10*	0.71 (0.39-0.86)	0.7	1.8

[a] Maximum & mean standing balance scores on the non-dominant & dominant leg and maximum & mean sitting balance scores in the sagittal & frontal plane

[b] Z-value of the Wilcoxon signed ranks test

* Statistically significant difference between test 1 & 2 ($P < 0.05$)

** Statistically significant difference between test 1 & 2 ($P < 0.001$)

Graduated Sitting Balance Test

Figure 3B shows a Bland-Altman plot of the maximum sitting balance scores determined while testing balance capacity in the frontal plane. It can be seen that subjects' average scores of test 1 and 2 varied over almost the whole range of possible measurement outcomes. This was only the case for frontal plane testing. Sagittal plane balance scores ranged between 6 and 9 points, indicating a ceiling effect in the results. As with the results of the graduated narrow ridge test, maximum and mean balance scores, averaged over all subjects, were significantly higher on test 2 compared to test 1, indicating a systematic bias between the results of the two test sessions. The ICC's for these scores were also moderate, ranging from 0.57 – 0.74 (Table 3). SEM values ranged between 0.4 and 0.8 points, while MDC values varied between 1.0 and 2.2 points (Table 3). As for the graduated narrow ridge test, ICC's were larger for the mean balance scores compared to the maximum balance scores.

Seated Perturbation Test

Due to some technical problems with the gyroscope data, the results of one subject were left out of the analysis. In figure 3C and 3D, scatter plots are presented of TTS and $RMS\omega_{seat}$, the data being averaged over all four perturbation directions. These plots show that subjects on average scored lower during the second test session compared to the first on these variables. For almost all variables determined, mean values for test 2 were smaller than for test 1, except for the kinematic variables obtained in response to rightward perturbations (Table 4). With respect to TTS, which can be seen as the main performance measure of the seated perturbation test, a systematic bias was found for all perturbation directions, except for the leftward perturbations (Table 4). For the rest, a systematic bias was found for several kinematic variables, mainly for the backward perturbations and for the results averaged over all four perturbation directions (Table 4). Looking at the perturbation directions separately, ICC's for TTS ranged between 0.68 and 0.86, while the ICC was 0.91 when TTS was averaged over all four directions (Table 4). For the kinematic variables, ICC's varied between 0.55 and 0.89, with even higher ICC's when averaged over all perturbation directions (Table 4). SEM and MDC values were smallest when results were averaged over all directions.

Table 4. Average scores (standard deviations) of the variables obtained from the seated perturbation test for test 1 & 2; test statistics showing the difference between test 1 & 2; ICC, SEM & MDC values indicating reliability

		Mean (SD) test 1	Mean (SD) test 2	t-value df = 28	ICC (95% CI's)	SEM	MDC
B^{a}	ω_{seat} (°·s^{-1})	45 (13)	40 (13)	2.39*	0.83 (0.63-0.92)	5	15
	ω_{trunk} (°·s^{-1})	30 (22)	24 (9)	-2.30^{b}*	0.55 (0.04-0.79)	10	28
	RMSω_{seat} (°·s^{-1})	28 (4)	26 (5)	2.59*	0.79 (0.55-0.90)	2	6
	RMSω_{trunk} (°·s^{-1})	17 (6)	15 (5)	-3.06^{b}*	0.83 (0.63-0.92)	2	6
	TTS (ms)	1096 (220)	949 (182)	4.00**	0.68 (0.32-0.85)	113	314
F	ω_{seat} (°·s^{-1})	44 (12)	41 (11)	1.80	0.77 (0.50-0.89)	6	16
	ω_{trunk} (°·s^{-1})	35 (17)	29 (7)	-2.58^{b}*	0.57 (0.07-0.80)	8	22
	RMSω_{seat} (°·s^{-1})	33 (4)	31 (4)	2.21*	0.81 (0.60-0.91)	2	5
	RMSω_{trunk} (°·s^{-1})	23 (5)	22 (4)	-1.07^{b}	0.78 (0.54-0.90)	2	6
	TTS (ms)	1229 (156)	1143 (167)	3.04*	0.72 (0.40-0.87)	86	237
L	ω_{seat} (°·s^{-1})	40 (11)	39 (10)	0.62	0.81 (0.59-0.91)	5	13
	ω_{trunk} (°·s^{-1})	34 (12)	31 (12)	2.40*	0.88 (0.75-0.94)	4	11
	RMSω_{seat} (°·s^{-1})	29 (5)	29 (5)	0.56	0.76 (0.49-0.89)	2	6
	RMSω_{trunk} (°·s^{-1})	25 (7)	24 (7)	1.28	0.86 (0.71-0.94)	3	7
	TTS (ms)	1260 (261)	1226 (248)	0.73	0.68 (0.31-0.85)	145	402
R	ω_{seat} (°·s^{-1})	40 (11)	40 (10)	0.02	0.86 (0.70-0.93)	4	11
	ω_{trunk} (°·s^{-1})	36 (13)	38 (15)	-1.06	0.89 (0.77-0.95)	5	13
	RMSω_{seat} (°·s^{-1})	36 (5)	36 (4)	-0.21	0.70 (0.35-0.86)	2	6
	RMSω_{trunk} (°·s^{-1})	30 (8)	30 (7)	-0.15	0.88 (0.75-0.94)	3	7
	TTS (ms)	1476 (322)	1369 (291)	2.70*	0.86 (0.71-0.94)	113	314
A	ω_{seat} (°·s^{-1})	42 (11)	40 (10)	2.01	0.90 (0.80-0.96)	3	9
	ω_{trunk} (°·s^{-1})	34 (12)	31 (8)	2.41*	0.87 (0.71-0.94)	4	11
	RMSω_{seat} (°·s^{-1})	31 (3)	31 (3)	2.84*	0.92 (0.83-0.96)	1	3
	RMSω_{trunk} (°·s^{-1})	24 (4)	23 (4)	2.82*	0.94 (0.88-0.97)	1	3
	TTS (ms)	1265 (171)	1172 (178)	5.12**	0.91 (0.82-0.96)	51	142

[a] Direction of perturbations: B = backward; F = forward; L = leftward; R = rightward; A= average of all four directions

[b] *Z*-value of the Wilcoxon signed ranks test

* Statistically significant difference between test 1 & 2 ($P < 0.05$)

** Statistically significant difference between test 1 & 2 ($P < 0.001$)

To investigate the relationship between the results of the narrow ridge balance test and the graduated sitting balance test, Pearson correlation coefficients were calculated between all standing balance scores and frontal plane sitting balance scores. Correlations ranged from 0.13 – 0.32, all being non-significant. Frontal plane sitting balance scores correlated significantly with frontal plane TTS (TTS of left- and rightward perturbations were averaged) obtained in the seated perturbation test, with correlations of -0.51 and -0.46 for maximum and mean sitting balance scores, respectively. Furthermore, frontal plane TTS also correlated significantly with standing balance scores for the non-dominant leg, the correlations being -0.63 and -0.54 for maximum and mean standing balance scores, respectively. Spearman correlation coefficients between sagittal plane balance scores and sagittal plane TTS were low and non-significant.

Discussion

One of the aims of the present study was to investigate the test-retest reliability of two newly developed core stability testing procedures along with an adapted version of the narrow ridge balance test as developed by.[7] In a study like this, the question arises what level of reliability is considered to be clinically acceptable. Although there is no standard acceptable level of relative reliability, Landis & Koch[18] classified an ICC between 0.4 and 0.6 as moderate, between 0.6 and 0.8 as substantial and an ICC between 0.8 and 1.0 was interpreted as almost perfect. Using this classification scheme, ICC's for the maximum and mean balance scores of the narrow ridge balance test were substantial, while ICC's for the graduated sitting balance test scores were moderate to substantial. Looking at the results of the seated perturbation test, ICC's for TTS were substantial to almost perfect and ICC's for the kinematic variables were moderate to almost perfect, with the highest ICC's found when data were averaged over all four perturbation directions.

In the present study, a rather homogeneous sample of normal subjects was tested. It has to be taken into account that the magnitude of the ICC depends on the between-subject variability, while the SEM can be seen as a fixed characteristic of any measure that is largely independent of the subject population.[38] SEM values for balance scores ranged between 0.3 and 0.8 points. With respect to the seated perturbation test, SEM values for TTS varied between 51 and 145 ms, the value of 145 ms being 12% of the corresponding average TTS (averaged over test 1 and 2). Based on the SEM values, MDC values were calculated to determine the change in subject score that constitutes a clinically important difference. MDC values for balance scores ranged between 0.8 and 2.2 points. Within-subject variation and the related MDC values were largest for balance scores obtained during frontal plane testing in the graduated sitting balance test. With respect to the seated perturbation test, MDC values for TTS varied between 142 and 402 ms.

It is difficult to compare the present results with previous studies investigating postural control, mainly because of differences in measurement systems, protocols and outcome measures. Until now, only a few studies have reported test-retest reliability of postural stability measures. Van Daele et al.[35] investigated the reproducibility of several CoP-measures and angular torso data during unstable sitting in low back pain patients. Reproducibility was found to be rather moderate, with ICC's ranging between 0.11 and 0.93. Van Dieën et al.[36] studied test-retest reliability of 39 CoP-parameters during 30 s seated balancing, concluding that reliability was rather low with ICC's below 0.7.

The advantages of the narrow ridge balance test and the graduated sitting balance test used in the present study are their simplicity and low costs, which make them useful instruments to screen the balance capacity of a large number of subjects in a clinical setting. The systematic bias found for all balance scores points to a learning effect. Previous postural control studies already described the presence of such a learning effect, possibly caused by benefiting from the experience of the first trial or subjects' eagerness to improve their test score during the second trial.[16,35] A way to overcome the problem of a learning effect is to present subjects with one or more pretest familiarization trials.[16,38]

Besides the systematic bias, a ceiling effect was found for sagittal plane testing in the graduated sitting balance test. This disadvantageous effect can be eliminated by expanding the test using balance boards with circle segments with an even smaller diameter than 17.5 cm. In this respect, Lanzetta et al.[19] already indicated that subjects had more difficulty with frontal plane stability compared to sagittal plane stability in unstable sitting posture. In the sagittal plane, postural control is achieved through adjustments in both the hips and intervertebral joints of the lumbar spine, whereas the hips do not play a role in frontal plane postural control.[1] It has been reported that CoP-sway in the frontal plane is related to an increased risk of falling.[27] During walking and running, sagittal plane stability is primarily maintained by correct positioning of the swing limb with respect to the CoM, while lateral stability is provided by lateral placement of the feet in combination with lateral trunk control.[2] Therefore, lateral stability can be improved by optimizing trunk function.[12] The role of neuromuscular trunk control in lateral standing stability is also confirmed by the present results, showing significant correlations between standing balance scores for the non-dominant leg and frontal plane TTS while seated. These results, together with the significant correlations between seated frontal plane stability and frontal plane TTS, indicate that adequate reactive neuromuscular trunk control plays a role in stabilizing both standing and seated posture in the frontal plane. In this respect, Genthon & Rougier[12] already indicated that stability in both postures is partly regulated by the same type of processes, but that performance appears largely independent because of different biomechanical constraints.

To measure trunk function, we developed two sitting balance tests. Testing in a seated position is necessary to isolate trunk control from the control of the lower extremities. However, the question should be raised whether performance in these tests accurately reflects trunk control ability during daily tasks or sports activities.[17] The tests presented here are more dynamic and show higher reliability compared to observing and rating the performance on static exercises.[39] But the challenge remains to assess functional core stability by testing even more dynamic movements in sport specific contexts, thereby adequately quantifying aspects of performance and preserving the reproducibility of the results.[15,17] Such measures would be helpful to evaluate the effect of rehabilitation and training programs on the ability to stabilize the body's core.[15]

In conclusion, test-retest reliability of the three postural control tests investigated was moderate to substantial. To increase the reliability and responsiveness of the narrow ridge balance test and to eliminate the ceiling effect in the graduated sitting balance test, these tests can easily be extended with extra ridges or balance boards, thereby increasing between-subject variation in the test results. The mean balance scores on these two tests are more reproducible than the maximum scores and thus can be recommended as outcome measures. For the seated perturbation test, TTS as the main outcome measure seems to be a reliable indicator of performance, encompassing both speed and accuracy of the postural reaction. Future research in this area should focus on further developing and refining these measurement methods to eventually use them in assessing the effect of neuromuscular interventions on improving core and whole-body stability.

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5. The Effect of a Soccer-Specific Neuromuscular Training Program on Stability, Agility and Injury in Elite Youth Soccer

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Abstract

Various studies have investigated the injury-preventive and performance-enhancing effect of neuromuscular training programs (NMTP's), showing varying results. To get insight into the underlying mechanisms, research should focus on the influence of these NMTP's on improving stability. **Purpose:** The main aim of this study was to investigate the effect of a soccer-specific NMTP on improving whole-body and core stability. Besides, the effect of such a program on agility and injury occurrence was evaluated. **Methods:** Ninety elite young soccer players (ages 11-17) were team-randomized into an intervention and control group. The intervention group performed a 15 min NMTP on average twice a week for 23 weeks. Prior to, during and after the NMTP, all players performed whole-body and core stability tests and a slalom sprint test. New non-contact time-loss injuries sustained during the intervention period were recorded. Repeated measures ANOVA's were conducted to find any differences between the intervention and control group on the stability and agility test results. Possible differences in injury severity were evaluated using a Mann-Whitney U test. **Results:** Relevant trends were found in the data, indicating a positive effect of the NMTP on standing balance capacity, reactive core stabilizing control and slalom sprint performance in the elite youth soccer players, although differences in improvement between the intervention and control group were non-significant. With respect to injury, no significant difference in incidence or severity was found between both groups. **Conclusions:** Further research is recommended to further elucidate the effect of the soccer-specific NMTP on improving stability. Refined measurement methods implemented in lower-level target groups can produce more insight into the injury-preventive and performance-enhancing role of having a stable core.

Key Words

Core Stability, Postural Balance, Neuromuscular Control, Injury Prevention, Performance Enhancement

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Introduction

In recent years, there has been an increase in the use of core stability exercises in sports conditioning programs and many elite athletes conduct such exercises as part of their training program.[14] Although these exercises are popular, relatively little research has been undertaken to provide a scientific rationale for their use in healthy athletes.[38] Studies investigating the effectiveness of core training on optimizing performance are limited and show contradictory findings and conclusions.[14] Results may be conflicting because of a wide variety of exercises or subjects used, but the main problem is the lack of a valid and reliable method for measuring core stability. Without such a measure, it is impossible to draw conclusions about the effect of an improved ability to stabilize the body's core on the performance aspects of a certain sport.

In the context of other studies and the specific goals of this study we define core as being the centre of the functional kinetic chain that provides a foundation upon which the extremity muscles produce or resist forces.[2,38] Without adequate postural control, an athlete cannot optimally transfer energy to the extremities.[26] This might ultimately lead to mechanical damage or injury due to compensations for the lack of force production or the inability of the control system to adequately respond to abnormal loading events.[26] Poor balance control has been proposed as a risk factor for several lower extremity (ankle, knee) injuries.[12,24,37] In elite and sub-elite soccer, players are subjected to a high number of sudden loadings of the upper body. Decreased neuromuscular control of the core can lead to compensatory movement patterns, inefficient movement technique, overuse, strain and in the end injury.[9,40] Therefore, training programs designed to prevent injury should also focus at upper body postural control. For the purpose of the present study, core stability is defined as the ability of the neuromusculoskeletal system to control trunk position in labile situations or in the presence of disturbances.[2] An improved ability to control trunk position has the potential to decrease excessive forces exerted on the lower extremity, thereby decreasing the risk of injury.[40]

As stability depends on the quality of motor control, the primary objective of training the core is to improve neuromuscular coordination (recruitment patterns and reaction time), thereby improving balance capacity.[15] Balance exercises can be considered as a type of core stability training in a way that the core musculature is activated while performing these exercises to stabilize the lumbar spine and maintain upright posture.[38] Balance is skill-specific and can be improved through refinements in neural programming.[38] In this respect, dynamic sport-specific exercises serve to solidify a neuromuscular engram specific to the activities performed.[8] According to Staron et al.,[35] neural adaptations may include more efficient neural recruitment patterns, improved synchronization of motor units, faster nervous system activation and a lowering of neural inhibitory reflexes. Training can also have important effects on both anticipatory postural adjustments (APA's) and postural reactions.[23] In acquiring an APA, feedback postural reactions are transformed into feedforward control associated with the movement performed.[23] Some studies already documented training-induced changes in these preprogrammed responses.[3,22] Inter- and intramuscular coordination is improved, resulting in precisely regulated contractions of the relevant muscles.[5] These long-lasting adaptations in sensory-motor control underlie improvements in motor skills.[30] In training the core, an athlete progresses from conscious (cortical) postural awareness and control to unconscious (sub-cortical) control.[25] The faster sub-cortical control system can lead to more adequate postural muscle responses.[25] An athlete then becomes more dependent on reaction mechanics in maintaining dynamic core stability, with postural reflexes playing a very important role.[32] In this respect, proprioceptive exercises may increase the sensitivity of muscle spindles and the position sense of the core muscles, leading to shortened muscle onset times and more efficient preprogrammed responses.[20,29,38] In the end, better movement control may lead to improved performance and reduced injury risk.

Spinks & McClure[34] highlighted the significant injury incidence in youth participating in soccer. Adolescents are particularly susceptible to a range of hard- and soft-tissue injuries, because they are in a process of major physiological change. It is recommended that injury prevention programs focusing on neuromuscular control, technique and balance training be implemented in young players who have not yet fully established their basic motion patterns.[33] In this respect, several neuromuscular training programs (NMTP's), mainly consisting of a variety of balance exercises, have been designed to improve postural control by challenging and enhancing the neuromuscular system. The target of these programs is to improve body control and motor skills.[27] Programs consist of sports-related exercises that can be performed in a warm-up setting to prepare the neuromuscular system for sports specific maneuvers.[1,27] With respect to soccer, an example of such a structured warm-up program is FIFA's 'The 11', containing exercises that among others focus on core stabilization, proprioception and plyometrics to improve coordination and reaction time.[18,19] Studies investigating the effect of 'The 11' on injury prevention and performance enhancement showed few positive results, partly due to low compliance with the program.[18,19,36] Most of these intervention studies focused on adolescent female players and positive effects were mainly found at a low skill playing level. Meta-analysis by Yoo et al.[39] showed that other similar neuromuscular training interventions were effective in preventing anterior cruciate ligament (ACL) injury in adolescent female athletes. In addition, a review by Hrysomallis[17] concluded that such multifaceted interventions reduced the risk of ankle and knee injury in various team sports, better than just a balance training intervention. Research is required to investigate the relative contribution of the balance component of these multifaceted interventions to injury prevention. Some studies found a significant relationship between poor balance ability and an increased risk of ankle injuries.[24,37] In addition, some studies revealed improved dynamic balance and single-limb postural stability in response to a NMTP,[15,28] while another study found a reduced re-injury risk, despite a lack of improvement in balance capacity.[16]

As far as the authors are aware no study has looked at examining the effect of a NMTP on the ability to stabilize the core. To investigate whether the injury-preventive effect of NMTP's is due to improvements in the capacity to stabilize the body's core, reliable measurements have to be used to assess neuromuscular control of the core muscles. Therefore, the aim of the present study was to investigate the effect of a soccer-specific NMTP on postural stability and the capacity to stabilize the core in elite male youth soccer athletes. In addition, it is also of clinical relevance to investigate the effect of such an intervention on performance and injury rates. In a sport like soccer, postural stability and optimal balance control are essential to perform at a high level without suffering a musculoskeletal injury.[20] Soccer is a contact sport requiring a variety of skills at different intensities with quick, ballistic and powerful agility movements.[36] Typical movement patterns consist of cutting movements, rapid accelerations and decelerations, turns and jumps.[15] Based on this, it was also investigated whether the soccer-specific NMTP had an effect on a player's level of agility and on injury occurrence.

Methods

Subjects

The sample of this study consisted of 90 young soccer players (ages 11-17) playing for six different soccer teams, all being part of the youth soccer academy of a single Dutch premier league club. All teams participated at the highest or second highest level of their respective age-category in the Dutch junior competition during the 2009/2010 season. Teams were allocated to either the intervention (INT, three teams) or control (CON, three teams) group, based on age-matching. Players' body weight and height were measured on a monthly basis by the club's medical staff. There were no significant differences in age, height or weight between INT and CON (Table 1). Players with a major injury at the start of the intervention were excluded. In addition, goalkeepers were excluded because of their different training regime. Implementation of the research design was approved by the head of the youth soccer academy. All soccer players volunteered for this study and signed an informed consent form before the first measurement session. The study was approved by the local ethics committee of the Medical Faculty of the University Medical Center Groningen, University of Groningen.

Table 1. Subject data for separate teams and for INT and CON

	Team (n)	Age (years)[b]	Weight (kg)[b]	Height (m)[b]	Training exposure (h)[c]	Match exposure (h)[c]
INT	**U-13 (14)**	12.4 (0.4)	42.7 (5.3)	1.56 (0.05)	6.0 / 5.4	0.9 / 1.4
	U-14 (15)	13.7 (0.2)	46.9 (4.7)	1.61 (0.06)	6.3 / 6.0	1.3 / 1.3
	U-17 (16)	16.4 (0.5)	65.8 (8.6)	1.75 (0.05)	6.5 / 6.8	1.2 / 1.7
	Total (45)	14.3 (1.7)	52.3 (12.1)	1.64 (0.10)	6.2 / 6.1	1.1 / 1.5
CON	**U-12 (13)**	11.7 (0.2)	38.1 (3.4)	1.47 (0.03)	4.7 / 4.3	0.7 / 1.3
	U-15(16)	14.7(0.3)	57.1 (6.9)	1.69 (0.05)	6.3 / 5.7	1.1 / 1.3
	U-16(16)	15.7 (0.4)	59.8 (7.1)	1.73 (0.07)	6.9 / 6.6	1.6 / 1.3
	Total (45)	14.2 (1.7)	52.6 (11.2)	1.64(0.13)	6.0 / 5.6	1.1 / 1.3

[a] U- = under the age indicated

[b] Values are mean (standard deviation)

[c] Average number of training hours per player per week before and after the start of the mid-intervention measurement session

Intervention

The competitive season lasted from early September until mid-May. During the competition period, from early November till mid-May, the teams in the INT group followed a soccer-specific dynamic NMTP, on average twice a week with 15 minute sessions under supervision of their coach. The intervention period was interrupted by a 4-week winter break without regular training and matches, from mid-December until mid-January. Prior to (September/early October), during (February/early March) and after (May/early June) the intervention, both INT and CON performed a battery of stability tests to measure whole-body stability and core stability and a slalom sprint test to measure agility. The intervention period lasted 10 weeks from the start of the intervention till the start of the second measurement moment and another 13 weeks until the end of the intervention.

The NMTP was based on exercises and prevention techniques used in previous studies.[11,33] The precise content of the NMTP (see appendix A, indicating the amount of training exercises performed by the intervention teams, together with short explanations of the exercises performed) was developed in collaboration with the coordinator of the youth soccer academy and exercises were designed and adapted to become soccer-specific and easy to include during regular practice sessions at no cost. Exercises focused on motor skills and body control and prepared the neuromuscular system for soccer-specific maneuvers. The main features of the NMTP were balance training, plyometrics and dynamic movement training. The INT teams performed the intervention exercises as part of their normal practice warm-up, whereas the CON teams completed their regular warm-up. Both groups were instructed to continue with their usual soccer-based training regime, with no intervention program or additional training for the CON group. Coaches of the INT teams were instructed on implementation of the intervention exercises and were asked to use the program at least twice a week during the intervention period. To facilitate understanding, compliance and correct execution, full written instructions on the technique of each exercise was provided to the coaches before the intervention started. The information material detailed each exercise and explained the correct performance for each, as well as common biomechanical mistakes. Next to the instruction booklet, coaches received an exercise diary to record the content and duration of each intervention session (see appendix A, indicating the amount of training exercises performed by the intervention teams, together with short explanations of the exercises performed). Coaches were instructed to provide progression in level of difficulty of the exercises, from simple to complex.

Stability

During the three measurement sessions all subjects performed a battery of stability tests to measure whole-body stability and core stability. The test battery included three test stations and was completed within 30 min. Groups of three subjects were tested in rotation and the tests were conducted in a random order. Prior to testing, body weight was measured. Whole-body stability was assessed using an adapted version of the narrow ridge balance test as developed by Curtze et al.[6] In this test, subjects were asked to maintain one-leg standing balance for 20 s on ridges of gradually decreasing width that were oriented in dorsoventral direction. Balance was assessed with subjects wearing indoor soccer shoes or sneakers with a flat sole. Mean standing balance scores for both the dominant and non-dominant leg were averaged and subsequently analyzed, with a possible range from 3 to 9 points. Core stability and robustness were assessed using the graduated sitting balance test and the seated perturbation test, respectively.[4] In the graduated sitting balance test, subjects were asked to maintain frontal plane sitting balance for 20 s on sitting boards with circle segments of gradually decreasing diameter mounted underneath, allowing the seat to roll over a table surface. Mean frontal plane sitting balance scores, with a possible range from 3 to 9 points, were taken as outcome measures. In the seated perturbation test, stable posture was perturbed by a sudden rotation of the sitting board, caused by the activation of a pneumatic cylinder underneath the seat. In response to this perturbation, subjects had to return to the equilibrium position as quick and accurate as possible by making corrective trunk movements. The test comprised 30 random perturbations in the frontal plane (15 leftward and 15 rightward), the first 10 perturbations forming a practice trial. There was a random time interval of 5-8 s in between subsequent perturbations. The perturbations consisted of 100 ms force impulses. The pressure of the pneumatic cylinder, and thereby the magnitude of the perturbation moment, was proportional to the weight of the subjects. The force impulses created on average a perturbation moment of 0.7 and 0.8 $Nm \cdot kg^{-1}$ body weight for the left- and rightward perturbations, respectively. Angular velocity of the balance seat in response to the perturbations was measured using a gyroscope (Murata; sensitivity 0.67 $mV \cdot {}^{\circ -1} \cdot s^{-1}$, range ± 90 $^{\circ} \cdot s^{-1}$). From the seat gyroscope data, time to stabilization (TTS) was determined as the time it took a subject to sit still in the equilibrium state for at least 0.5 s after perturbation onset. TTS was determined using Matlab. For every perturbation direction, only the three perturbations with the smallest TTS were eventually taken into the analysis, to correct for a possible effect of fatigue or lack of concentration. Mean TTS for both the leftward and rightward perturbations were averaged and subsequently analyzed. A detailed description of all three test protocols can be found in Borghuis et al.[4] This study also indicated that test-retest reliability of the tests was moderate to substantial. Intraclass correlation coefficient (ICC) for standing balance scores obtained with the narrow ridge balance test was 0.86 when scores were averaged for both the dominant and non-dominant leg. ICC for the graduated sitting balance test was reported to be 0.71 and ICC for frontal plane testing in the seated perturbation test was found to be 0.93.[4]

Agility

In the three measurement sessions all subjects performed a slalom sprint test to measure agility. A detailed description of this test can be found in Lemmink et al.[21] Reliability of this test was reported to be high, with an intraclass correlation coefficient (ICC) of 0.91. In the present study, subjects only performed the test by slalom sprinting without a ball. All tests were conducted during subjects' normal training hours, on an artificial grass surface under comparable weather circumstances, with subjects wearing their normal playing footwear. Infrared timing gate systems were used at the start and finish line to record slalom sprint times to the nearest 0.01 s. Subjects performed two correct trials and the best time of these two trials was taken into the analysis. Because of several reasons (injury or leaving the youth soccer academy before measuring agility on the third measurement session), only 60 players were able to complete all three agility tests and were considered in the slalom sprint analysis.

Injuries

For the injury analysis, the club's medical team (physical therapists and team physician) recorded each injury and its circumstances using a web based database. The medical team was blinded to group allocation. All injuries were recorded using a standard form containing the following information: date of injury, injury type, anatomical location and side, mechanism of injury (traumatic or overuse) and when the injury occurred (match or training). From the injury database, all new non-contact time-loss injuries that occurred during the intervention period were determined and served as the main outcome measure. A non-contact time-loss injury is defined as any physical complaint sustained by a soccer player that resulted from a soccer match or training, occurring without any opponent soccer player movement in correlation with the injury incidence and resulting in a player being unable to take full part in future training or competition.[10] Both acute and overuse injuries were taken into the analysis. Recurrent injuries were not considered as separate injuries, but severity of these injuries was added to the severity of the first injury episode. Injury severity was determined based on days absent from soccer until the player was fully fit to take part again in organized training or match play. Injuries were classified according to length of absence from training and matches as slight (1-3 days), minor (4-7 days), moderate (8-28 days) and major (>28 days).[13]

Data regarding match and training exposure were collected at team level (Table 1). A team's training exposure (in player hours) was calculated as the number of training sessions multiplied by the average player attendance (number of team members minus two) and average training time (90 min per session). A team's match exposure (in player hours) was calculated as the number of matches multiplied by the number of players (11) and match duration (in hours). Pre-match warm-up sessions were recorded as training exposure. Total exposure was calculated as the sum of training and match exposure. Injury incidence was calculated as the number of injuries per 1000 player hours. The number of injured players, injury incidence and injury severity were compared between INT and CON.

Statistical Analysis

With respect to the stability and agility data, values for skewness and kurtosis and results of Kolmogorov-Smirnov tests indicated that all data were normally distributed. Changes in test scores for both INT and CON were first examined using bar graphs indicating the difference scores between the three measurement sessions. To investigate whether INT improved significantly more compared to CON on the stability and agility test results, repeated measures ANOVA's were conducted for each dependent variable separately with measurement session (T1, T2 & T3) as within-subjects factor and group (INT & CON) as between-subjects factor. To indicate the size of the intervention effect relative to the variability in test scores, Cohen's *d* values were calculated for test results on T3.

With respect to injuries, only injuries sustained in the U-14 till U-17 age categories (see Table 1) were taken into the analysis. Injuries for the U-12 and U-13 age categories were left out, because for the U-12 team injuries were recorded on a less regular basis, partly due a different training regime compared to the other five teams. To investigate whether the NMTP had a positive effect on injury severity, a Mann-Whitney *U* test was conducted with injury severity as dependent variable and group as between-subjects factor. To investigate whether there was a relationship between whole-body and/or core stability test scores on T1 and injury occurrence during the intervention period, pre-intervention test scores obtained with the narrow ridge balance test, the graduated sitting balance test and the seated perturbation test were compared between players who got injured during the intervention period and non-injured players using independent-samples t-tests. All statistical analyses were performed using SPSS software with $P < 0.05$ indicating statistical significance.

Results

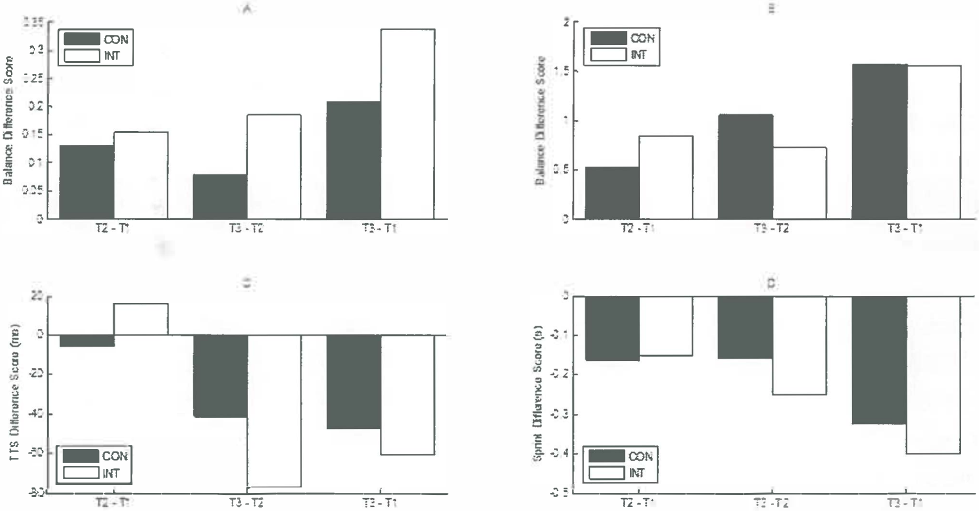

Figure 1. Mean difference scores between T1, T2 & T3 for **(A)** the narrow ridge balance test, **(B)** the graduated sitting balance test, **(C)** the seated perturbation test and **(D)** the slalom sprint test.

Players in the INT and CON group on average missed respectively 9.4% and 7.8% of their teams training sessions due to injury or illness. Figure 1 presents the effect of the intervention on the stability and agility test results. In figure 1A it can be seen that performance on the narrow ridge balance test improved more for INT compared to CON. This difference in improvement was mainly seen from T2 to T3. The same trend was seen for performance on the seated perturbation test (TTS, Fig. 1C) and the slalom sprint test (Fig. 1D), where negative values indicate performance improvement. Figure 1B shows that absolute improvement on the graduated sitting balance test was much higher for both groups compared to the absolute improvement on the narrow ridge balance test, although performance on both tests was determined using the same scoring system. Whereas INT improved more from T1 to T2, CON improved more from T2 to T3, such that there was no difference in improvement between both groups from T1 to T3 (Fig. 1B). Results of the repeated measures ANOVA's indicated no significant difference in improvement between INT and CON on the stability and agility parameters investigated and effect sizes determined for results on T3 were small (Table 2).

Table 2. Means and standard deviations for T1, T2 & T3, results of the repeated measures ANOVA's and Cohen's *d* values indicating effect sizes

		T1: Mean (SD)	T2: Mean (SD)	T3: Mean (SD)	F-value (df)	*P*	ES[b]
Standing balance	CON (44)[a]	6.00 (0.65)	6.13 (0.65)	6.21 (0.69)	0.906 (2,84)	0.408	0.14
	INT (43)	5.97 (0.59)	6.12 (0.55)	6.30 (0.66)			
Sitting balance	CON (44)	5.66 (1.30)	6.19 (1.31)	7.23 (1.12)	1.389 (2,85)	0.255	0.06
	INT (44)	5.73 (1.39)	6.58 (1.24)	7.30 (1.17)			
TTS (ms)	CON (44)	931 (160)	925 (172)	884 (156)	0.915 (2,84)	0.404	0.08
	INT (43)	934 (161)	949 (124)	872 (132)			
Slalom sprint time	CON (28)	13.75 (0.59)	13,59 (0.61)	13.43 (0.60)	0.522 (2,59)	0.596	0.29
	INT (32)	13.68 (0.58)	13.63 (0.53)	13.28 (0.39)			

[a] Number of subjects

[b] Effect Size: Cohen's *d* values for test results on T3

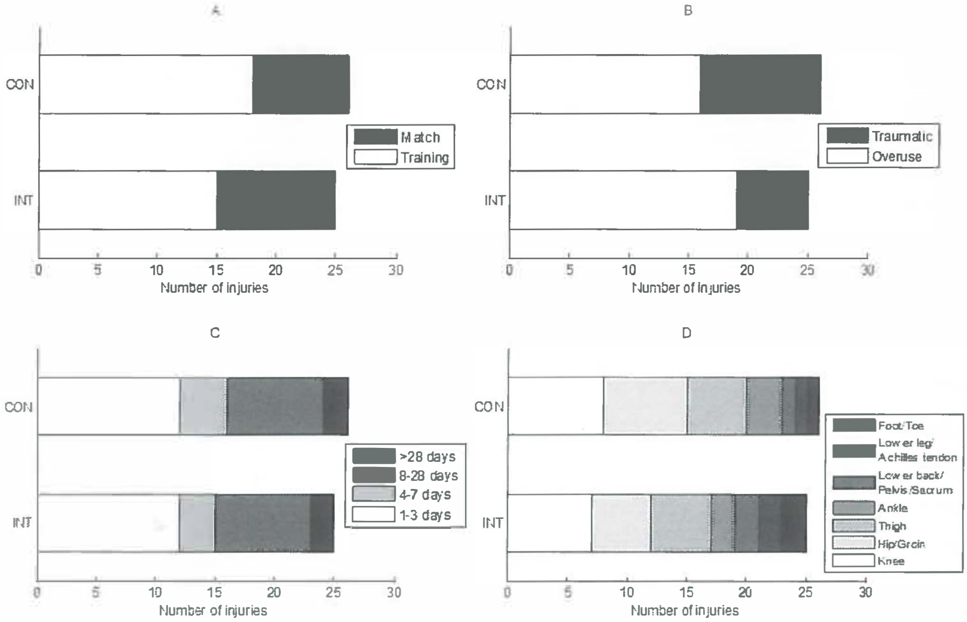

Figure 2. Number of injuries divided into **(A)** match vs training, **(B)** traumatic vs overuse and divided according to **(C)** severity and **(D)** location.

Figure 2 presents several classifications of the injuries sustained during the intervention period in the U-14 till U-17 age categories. During the intervention period, 26 and 25 new non-contact time-loss injuries occurred in CON and INT, respectively. The injury incidence was 12.1 and 14.2 per 1000 match hours and 4.3 and 3.7 per 1000 training hours for CON and INT, respectively. Players in the CON group sustained more traumatic injuries and injuries occurred more often during training compared to the INT group (Fig. 2A & 2B). Most of the injuries were located in the knee, hip/groin and thigh (Fig. 2D). Injury severity of most injuries was either slight or moderate (Fig. 2C). Results of the Mann-Whitney *U* test revealed no significant difference in injury severity between INT and CON (Z = -1.304; *P* = 0.192). Table 3 shows that there were no significant differences in pre-intervention core and whole-body stability test results between players who got injured during the intervention period and non-injured players. Looking at the mean values, injured players even performed better on the graduated sitting balance and the seated perturbation test compared to the non-injured players on T1 (Table 3).

Table 3. Independent t-test results for the differences in pre-intervention stability test scores between injured and non-injured players

	Mean T1 (SD)			
	Non-injured (31)[a]	Injured (32)	T-value (df)	*P* (two-tailed)
Standing balance	6.15 (0.67)	6.12 (0.60)	0.193 (61)	0.848
Sitting balance	5.76 (1.38)	5.99 (1.43)	-0.672 (61)	0.504
TTS (ms)	980 (190)	933 (151)	1.097 (61)	0.277

[a] Number of subjects

Discussion

The main aim of the present study was to investigate the effect of a soccer-specific NMTP on whole-body stability and the capacity to stabilize the body's core in elite male youth soccer athletes. Trends in the data indicated that the NMTP had a positive effect on standing balance capacity and reactive core stabilizing control. Performance on the narrow ridge balance test and seated perturbation test improved more for INT compared to CON from T2 to T3. Not finding this trend for the period from T1 to T2 could possibly be due to a shorter intervention interval (10 versus 13 weeks for respectively T1-T2 and T2-T3) in combination with a winter break just prior to the start of T2. Especially the 4-week winter break may have resulted in a decline of the effect of the NMTP. On the other hand, a reverse trend in the data was seen for performance on the graduated sitting balance test.

With respect to the effect of the NMTP on the soccer-specific performance aspect of agility, a similar trend in the data was seen as for the narrow ridge balance test and seated perturbation test. Despite the fact that INT performed faster on the slalom sprint test compared to CON at T1, INT nevertheless improved more from T2 to T3. The comparable trend in the data between standing balance and slalom sprint performance might indicate that heightened one-leg stability might carry over to the stance phase of running, thereby improving agility performance.

The present study also investigated the effect of the NMTP on injury occurrence. The relatively small amount of subjects and the inclusion of only new non-contact time-loss injuries resulted in a low number of injuries sustained during the intervention period. No significant differences in injury incidence and severity were found between INT and CON. Furthermore, the results indicated that the whole-body and core stability test scores obtained at T1 could not be used as predictive values for injury occurrence during the subsequent intervention period.

The main interest of the present study was the difference in performance improvement between INT and CON. Although positive trends were seen for standing balance, TTS and slalom sprint performance from T2 to T3, no significant differences in improvement were found for the stability and agility test results. Nevertheless, the positive trends may be very relevant for the population investigated. Although it becomes harder to find significant differences on various performance aspects between players acting at a higher level, small differences between elite players may be very important for a successful sports career.[7,31] With respect to the volume of the NMTP exercises performed, the question could be raised what the additional effect will be of twice a week 15 min soccer-specific NMTP in elite youth soccer athletes who train on average six hours a week. Increasing the volume of the exercises, for example by integrating the exercises in every training session's warm-up, may amplify the positive trends found in the present study.

The intention of the NMTP used in the present study was to use soccer-specific exercises, thereby making the program functional enough to translate into improvements in sports performance. This intention leads to balance exercises with body postures resembling postures adopted during regular soccer practice exercises, whereby the training content of INT and CON becomes more equal. This might have been disadvantageous in finding a significant effect of the program on the stability parameters tested. In addition, the lack of a significant effect may have also been due to the NMTP exercises being low-load exercises, mainly performed in a standing position. The intensity of the exercises may not have been sufficient to result in a significant improvement in test performance, especially for the core stability tests. Choosing more core-demanding exercises often goes at the expense of the training principle of specificity, as these exercises mainly focus on strength and endurance of the core muscles, instead of training neuromuscular control in a sport-specific way.[2]

One of the aims of neuromuscular training is to improve stability through a faster subcortical control system.[25] Reduced muscle reaction times and improved intermuscular coordination are important components in achieving transfer to sports skills.[15] According to the training principle of specificity, these adaptations are specific to the nature of the training stress.[38] At the same time, this principle of specificity also counts for the measurement techniques used. In this respect, the question remains whether the core stability measurement instruments used in the present study, with subjects adopting a seated posture, actually measure the subcortical neuromuscular core control that is trained in a standing position. Although the instruments give an indication of an individual's level of core stability, a true understanding of the stabilizing role of the body's core during whole-body movements while playing sports requires sport-specific testing. The challenge in this respect is to find a practical way to isolate core stability from the stabilizing activities of the lower extremities, while testing in an upright, sport-specific posture.

The intervention consisted of a practical and cost-effective on-the-field warm-up program, requiring only traditional soccer equipment. As the program was made part of the already existing training programs in each soccer team, compliance was very high. Both INT and CON showed improvement on the stability and agility test results. It is possible that over the intervention period any training benefits may be superseded by changes thanks to growth and maturity. Another factor affecting the test outcomes on the stability tests might be a possible learning effect. Although a previous test-retest reliability study showed such a learning effect when performing the test twice with one week in between,[4] this effect is not likely in the present study because of the much longer time in between the three measurement sessions. Nevertheless, for future research it is recommended to start with a practice measurement session before T1 to improve reliability.

In this study, only elite male youth soccer athletes were tested. Based on previous research and knowing the biomechanical differences between male and female athletes, it is likely that female athletes and athletes playing at a lower level would benefit more from a soccer-specific NMTP.[1,33] In addition, the test battery used in the present study may not have detected all potential improvements in stability in the elite youth soccer athletes due to a lack of sensitivity. To make the stability measurement instruments more sensitive, the narrow ridge balance test and the graduated sitting balance test can easily be expanded using extra ridges and balance boards, thereby creating extra levels of test difficulty.

Based on the positive trends in the data, future research is recommended to further elucidate the effect of the soccer-specific NMTP on improving stability. Although no significant effects were found for the stability and agility parameters investigated, the positive trends for the INT group may be very important for a successful sports career in the present group of highly trained elite youth soccer players. To amplify the positive effect of the NMTP, the volume and intensity of the exercises should be increased and exercises should be performed on a regular and continuous basis. Furthermore, measurement instruments can be made more sensitive and it would be interesting for future research to study the effect of the NMTP in lower level or female athletes. To make statements about the injury-preventive effect of the NMTP, research should be conducted with a larger group of subjects over a longer period of time. Despite widespread acceptance that core stability impacts on sports performance, further research is required to establish whether this can be substantiated. As the present study attempted, future research should be conducted based on clear definitions and using valid and reliable methods to summarize the effectiveness of different core exercises. This will contribute to the development of more effective training programs with respect to injury prevention and sports performance improvement.

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Appendix A

Table 1. Amount of training exercises performed by the intervention teams

Exercise	U-14: 53 (21 / 32)[a]	U-15: 43 (18 / 25)	U-17: 40 (18 / 22)
1. One-leg balance, simple variant.	19 (7 / 12)[b]	15 (8 / 7)	7 (3 / 4)
2. One-leg balance, advanced variant.	17 (5 / 12)	12 (5 / 7)	9 (4 / 5)
3. Blind one-leg balance simple variant.	15 (6 / 9)	15 (8 / 7)	7 (3 / 4)
4. Blind one-leg balance advanced variant.	14 (4 / 10)	12 (5 / 7)	9 (4 / 5)
5. One-leg balance with leg swings.	9 (4 / 5)	15 (8 / 7)	7 (3 / 4)
6. Runners' poses.	7 (2 / 5)	5 (2 / 3)	9 (4 / 5)
7. One-footed heel raises.	9 (4 / 5)	10 (6 / 4)	7 (3 / 4)
8. Cross-country skiing.	11 (3 / 8)	7 (2 / 5)	9 (4 / 5)
9. One-leg balance while holding a ball up.	29 (10 / 19)	12 (4 / 8)	16 (7 / 9)
10. The plank.	8 (3 / 5)	10 (5 / 5)	6 (3 / 3)
11. Disturbed one-leg balance.	8 (3 / 5)	6 (3 / 3)	6 (3 / 3)
12. Chest-passing in single-leg stance.	8 (3 / 5)	3 (2 / 1)	6 (3 / 3)
13. Forward-bend in single-leg stance.	2 (0 / 2)	3 (2 / 1)	6 (3 / 3)
14. Figure-eight's in single-leg stance.	2 (0 / 2)	3 (2 / 1)	6 (3 / 3)
15. Heading in single-leg stance.	0 (0 / 0)	9 (4 / 5)	9 (4 / 5)
16. Volley in single-leg stance.	12 (6 / 6)	10 (4 / 6)	9 (4 / 5)
17. Control and volley in single-leg stance.	12 (6 / 6)	6 (1 / 5)	9 (4 / 5)
18. Jumping header in single-leg stance.	0 (0 / 0)	6 (2 / 4)	9 (4 / 5)
19. Jumping volley in single-leg stance.	0 (0 / 0)	4 (2 / 2)	9 (4 / 5)
20. Up-down rotation.	12 (6 / 6)	8 (4 / 4)	1 (1 / 0)
21. Left-right rotation.	12 (6 / 6)	5 (2 / 3)	1 (1 / 0)
22. Sit-ups.	0 (0 / 0)	5 (2 / 3)	1 (1 / 0)
23. React and turn.	4 (2 / 2)	6 (2 / 4)	1 (1 / 0)
24. Bending an 8-point star.	4 (1 / 3)	0 (0 / 0)	0 (0 / 0)
25. Jumping an 8-point star.	0 (0 / 0)	0 (0 / 0)	0 (0 / 0)
26. Reactively changing direction.	7 (3 / 4)	9 (2 / 7)	8 (3 / 5)
27. Aerial duel.	7 (3 / 4)	6 (2 / 4)	8 (3 / 5)
28. Left-right jumping.	4 (1 / 3)	7 (2 / 5)	8 (3 / 5)
29. Zigzag shuffle.	7 (3 / 4)	6 (2 / 4)	8 (3 / 5)
30. Bounding.	0 (0 / 0)	1 (0 / 1)	0 (0 / 0)
31. Somersaulting.	6 (2 / 4)	0 (0 / 0)	0 (0 / 0)
32. Follow the leader.	4 (1 / 3)	4 (2 / 2)	8 (3 / 5)

[a] Amount of 15 min training sessions: Total (Before T2 / After T2)

[b] Number of times the exercise is performed: Total (Before T2 / After T2)

Explanation of the exercises performed

Individual one-leg balance exercises to perform on the field with a large group of players:

1. One-leg balance, simple variant.

Materials: *- stopwatch*

Action: Stand on your left foot with relaxed, upright posture and with your right leg flexed at the knee, so that the right foot is off the floor. Your left, weight-bearing leg should be lightly flexed at the knee, hip and ankle, as they would be when your left foot is on the ground during the act of running. Simply hold this position for 30 s, rest for 10-20 s and then repeat once more. After a brief rest, complete two similar reps with your right leg as the weight-bearing limb.

Important: Always keep your knee slightly bent. Do not let the knee buckle inwards. Keep your pelvis horizontal and do not let it tilt to the side. Keep your weight on the ball of the foot or lift your heel from the ground.

2. One-leg balance, advanced variant.

Materials: *- stopwatch*

Action: As 'one-leg balance, simple variant', except that you should swing your arms back and forth vigorously, mimicking the arm action associated with running, as you stand one-footed. Complete the same number of sets and reps you used for regular one-leg balances, so 30 s twice for each leg.

Important: Always keep your knee slightly bent. Do not let the knee buckle inwards. Keep your pelvis horizontal and do not let it tilt to the side. Keep your weight on the ball of the foot or lift your heel from the ground.

3. Blind one-leg balance, simple variant.

Materials: *- stopwatch*

Action: As 'one-leg balance, simple variant', except that you must keep your eyes completely closed as you perform the routine. Closing your eyes removes the strong, balance-enhancing input from your visual system and forces your nervous system to rely more heavily on your vestibular and somatosensory systems to produce balance. Complete the same number of sets and reps you used for regular one-leg balances, so 30 s twice for each leg.

Important: Always keep your knee slightly bent. Do not let the knee buckle inwards. Keep your pelvis horizontal and do not let it tilt to the side. Keep your weight on the ball of the foot or lift your heel from the ground.

4. Blind one-leg balance, advanced variant.

Materials: *- stopwatch*

Action: As 'one-leg balances, advanced variant', except that you must keep your eyes completely closed as you perform the routine. Closing your eyes removes the strong, balance-enhancing input from your visual system and forces your nervous system to rely more heavily on your vestibular and somatosensory systems to produce balance. Swing your arms back and forth vigorously, mimicking the arm action associated with running, as you stand one-footed. Complete the same number of sets and reps you used for regular one-leg balances, so 30 s twice for each leg.

Important: Always keep your knee slightly bent. Do not let the knee buckle inwards. Keep your pelvis horizontal and do not let it tilt to the side. Keep your weight on the ball of the foot or lift your heel from the ground.

5. One-leg balance with leg swings.

Materials: *none*

Action: Stand with your weight fully supported on your left leg. Begin by flexing your right hip and raising your right knee up to waist height (so that your right thigh is parallel to the ground), with your right knee flexed to approximately 90 degrees or a little more. Perform this action reasonably quick, so that your leg 'swings up' to this top position, rather than being slowly lifted. Continue the exercise by swinging your right leg downwards and backwards until your right leg is extended behind your body (as if following through on a running stride). Your right knee should be completely extended at the end of this backswing, that is, your right leg should be nearly straight at the back of the swing (just as it would be after take-off during a sprint stride). Once you have reached full extension, drive your right leg forward, flexing your right knee as you do so, until your right thigh is once again in front of you and parallel with the floor. Be sure to coordinate arm activity with your leg swings. That is, as your right leg swings forward and up, your left arm should also swing ahead, as it would do during running. As your right leg moves backward, your left arm also retreats. Try to keep the overall feeling of the exercise as close to the sensation of running as possible. Repeat this forward and backward action 30 times while gradually increasing the speed and range of motion of the movement. Rest briefly, and then repeat 30 more times with your right leg. Once you have completed two sets of 30 reps with your right leg, carry out the same movements with your left leg.

Important: Make sure you are sustaining a relaxed posture, with your upper body upright and your gaze directed ahead of you, not at your feet. You should try to achieve the same posture you would utilize during running. Always keep your knee slightly bent. Do not let the knee buckle inwards. Keep your pelvis horizontal and do not let it tilt to the side.

6. Runners' poses.

Materials: *none*

Action: Stand relaxed with erect body posture, with your feet roughly under your shoulders. Then swing your right thigh ahead and upward until it is parallel with the floor, with your right knee flexed to approximately 90 degrees or a little more. Keep your weight on the ball of the foot and lift your heel from the ground. As you swing your thigh ahead and up, simultaneously bring your left arm forward, as you would do during a normal running stride. Hold this position for a couple of seconds, while maintaining relaxed stability and balance, and then bring your right foot back to the ground and your left arm back to a relaxed position at your side (that completes one 'pose'). Perform 14 more pose reps with your right thigh and then switch over to the left leg for 15 poses. As you get better at doing this exercise, gradually speed up the thigh-lift movement and also elevate the thigh beyond the parallel-with-the-ground position (so that the exercise eventually becomes a high-knee-lift pose).

Important: Make sure you are sustaining a relaxed posture, with your upper body upright and your gaze directed ahead of you, not at your feet. You should try to achieve the same posture you would utilize during running. Always keep your knee slightly bent. Do not let the knee buckle inwards. Keep your pelvis horizontal and do not let it tilt to the side.

7. One-footed heel raises.

Materials: *none*

Action: Stand with relaxed, erect posture, with all your body weight supported on your right foot (your left leg should be flexed at the knee so that your left shin is roughly parallel with the ground and your left foot is off the ground). The hip, knee and ankle of the right leg should be slightly flexed. Then contract your right calf muscles as strongly as possible, so that your right heel rises vertically and you rock forward onto your right toes. Hold this tip-toe position for a second or two (all of your body weight should be supported by the toes and forefoot of your right foot). Then let your right heel return to the ground smoothly and with moderate speed. Once your right foot hits the ground, instantly 'explode' upward, rocketing back up to the tip-toe stance. Again, hold the weight-on-toes position for a second or two and then continue the described movements. As you do the exercise, move rhythmically and without hesitation (except at the tip-toe position) and try to maintain good balance, posture and stability at all times. After completing 15 reps on your right foot, perform 15 reps with your left.

Important: Make sure you are sustaining a relaxed posture, with your upper body upright and your gaze directed ahead of you, not at your feet. You should try to achieve the same posture you would utilize during running. Always keep your knee slightly bent. Do not let the knee buckle inwards. Keep your pelvis horizontal and do not let it tilt to the side.

8. Cross-country skiing.

Materials: *none*

Action: Stand on the right leg and let the other leg hang relaxed. Bend the knee and hips slightly, so that the upper body leans forward. When viewed from the front, hip, knee and foot of the supporting leg should be in a straight line. Flex and extend the knee of the supporting leg and swing the arms in opposite directions in the same rhythm. Flex the knee as much as possible, but keep weight balanced on the entire foot. On extension, never lock the knee. Keep pelvis and upper body stable and facing forwards. Perform 15 times on the right leg, then 15 times on the left leg.

Important: Keep pelvis horizontal and do not let it tilt to the side. Do not let knee buckle inwards.

9. One-leg balance while holding a ball up.

Materials: *- stopwatch + 1 ball per player*

Action: Stand on your non-dominant leg while holding a ball up in the air with your dominant foot for 30 seconds, without making corrective steps. The kicking foot should not hit the floor. Complete another 30 seconds with your dominant leg as the weight-bearing limb.

Core and balance exercises to perform in pairs on the field with a large group of players:

10. The plank.

Materials: *- stopwatch + 1 ball per 2 players*

Action: Pair up with a teammate. Lie on your stomach, facing each other. Support the upper body with your hands, placing them shoulder width apart. Place the feet vertical to the ground. Align your back and legs in a straight line. Then try to strike each other's hands, so that the upper body of your teammate falls down on the floor. Keep this up for 20 s, rest for 10-20 s and then repeat once more. A variation is to throw a ball to each other with your left hand, each player throwing and catching five times. Repeat with your right hand.

Important: Align your back and legs in a straight line.

11. Disturbed one-leg balance.

Materials: - stopwatch

Action: Pair up with a teammate. Stand on your left foot with relaxed, upright posture and with your right leg flexed at the knee so that the right foot is off the floor. While facing each other, grasp your opponent's wrist and try to disturb his balance using short pulling movements. Keep this up for 20 s, rest for 10-20 s and then repeat once, now standing on your right foot.

12. Chest-passing in single-leg stance.

Materials: - 1 ball per 2 players

Action: Two players face each other at a distance of 3 m, both standing on their right leg. Knee and hips should be slightly bent. Keep your weight on the ball of the foot or lift your heel from the ground. When viewed from the front, hip, knee and foot of the supporting leg should be in a straight line. Throw a ball back and forth: standing on the right leg means throwing with the left arm and vice versa. Catch the ball with both hands and throw it back with one hand. The quicker the exchange of the ball, the more effective the exercise. Perform 15 times on the right leg, then 15 times on the left leg.

Important: Always keep your knee slightly bent. Do not let your knee buckle inwards.

13. Forward-bend in single-leg stance.

Materials: - 1 ball per 2 players

Action: As 'chest-passing in single-leg stance'. Before throwing back, touch the ball to the ground without putting weight on it. Perform 10 times on the right leg, then 10 times on the left leg.

Important: When viewed from the front, hip, knee and foot of the supporting leg should be in a straight line. Keep weight only on the ball of the foot or lift your heel from the ground.

14. Figure-eight's in single-leg stance.

Materials: - 1 ball per 2 players

Action: As 'chest-passing in single-les stance'. Before throwing back, swing the ball in a figure-8 through and around both legs: first around the supporting leg with the upper body leaning forward and then around the other leg while standing as upright as possible. Perform 10 times on the right leg, then 10 times on the left leg.

Important: When viewed from the front, hip, knee and foot of the supporting leg should be in a straight line. Always keep your knee slightly bent and do not let it buckle inwards.

15. Heading in single-leg stance.

Materials: - 1 ball per 2 players

Action: As 'chest-passing in single-leg stance'. One player throws a ball and the other player heads it back. After 10 reps, roles are changed. Both players perform the exercise on both their dominant and non-dominant leg. A variation is to perform the header while making a one-leg jump in place.

Important: Always keep your knee slightly bent. Do not let your knee buckle inwards.

16. Volley in single-leg stance.

Materials: - 1 ball per 2 players

Action: As 'chest-passing in single-leg stance'. Now the ball is volleyed back with the inner side or instep of the foot into the hands of the thrower. Again, both players perform 10 reps on both their dominant and non-dominant leg.

Important: Always keep your knee slightly bent. Do not let your knee buckle inwards.

17. Control and volley in single-leg stance.

Materials: - 1 ball per 2 players

Action: As 'chest-passing in single-leg stance'. One player throws a ball at chest- or knee-height. The other player controls the ball with his chest or knee and volleys it back with the inner side or instep of the foot into the hands of the thrower. Again, both players perform 10 reps on both their dominant and non-dominant leg.

Important: Always keep your knee slightly bent. Do not let your knee buckle inwards.

18. Jumping header in single-leg stance.

Materials: - 1 ball per 2 players

Action: Two players face each other at a distance of 4 m, both standing on their right leg. Knee and hips should be slightly bent. Keep the weight on the ball of the foot or lift the heel from the ground. When viewed from the front, hip, knee and foot of the supporting leg should be in a straight line. The exercise is performed as in one-leg balance with heading, except that the heading player is now making a forward jump while heading the ball back, landing on his right leg. Then the heading player jumps backward on his right leg. After 10 reps, roles are changed. Both players perform 10 reps on both their dominant and non-dominant leg.

Important: Always keep your knee slightly bent. Do not let your knee buckle inwards.

19. Jumping volley in single-leg stance.

Materials: *- 1 ball per 2 players*

Action: As 'one-leg balance with jumping header'. Now the ball is volleyed back with the inner side or instep of the foot of the non-weight-bearing leg into the hands of the thrower. Again, each player performs 10 reps on both their dominant and non-dominant leg.

Important: Always keep your knee slightly bent. Do not let your knee buckle inwards.

20. Up-down rotation.

Materials: *- stopwatch + 1 ball per 2 players*

Action: Pair up with a teammate of approximately the same length. Stand with your backs against each other with some space in between. Holding a ball with two hands, hand it over to your teammate, over your head. Then your teammate hands it over down between the legs. Repeat this cycle as fast as possible for 20 s, rest for 10-20 s and then repeat once more handing over the ball in the opposite direction.

21. Left-right rotation.

Materials: *- stopwatch + 1 ball per 2 players*

Action: Pair up with a teammate of approximately the same length. Stand with your backs against each other with some space in between. Holding a ball with two hands, hand it over to your teammate by rotating the trunk, so that the ball moves in a circle around both players. So one player hands over the ball rotating leftward, while the other rotates rightward receiving it. Then the receiver rotates leftward to hand the ball over at the other side of the body. Repeat this cycle as fast as possible for 20 s, rest for 10-20 s and then repeat once more handing over the ball in the opposite direction.

22. Sit-ups.

Materials: *- stopwatch + 1 ball per 2 players*

Action: Pair up with a teammate of approximately the same length. Both lie down on your back, facing each other with legs stretched and the sole of the feet against each other. One player taps the ball to the ground behind his head, performs a sit-up and hands the ball over to his teammate, who subsequently performs the same action. The player without a ball performs the same action as the player with ball. Repeat this cycle as fast as possible for 20 s, rest for 10-20 s and then repeat once more.

23. React and turn.

Materials: - stopwatch + 5 cones

Action: Pair up with a teammate. Use four cones to mark out a square of 3 x 3 m. Place a cone in the center of the square. This is your starting position. Give each corner a number and remember it. Have your teammate call numbers at random. Sprint to the corner shouted and return to the middle, after which immediately a new number is shouted. Each player performs three series of 10 s.

24. Bending an 8-point star.

Materials: - 8 cones

Action: Mark an 8-point star with cones. The size of the star depends on the length of the players. Stand in the middle of the star and balance on your non-dominant leg. By bending, touch all eight cones with the toes of your dominant leg, one by one. The deeper you bend and the faster you perform the exercise, the more difficult it becomes. After having touched all cones, repeat the exercise on your dominant leg.

Important: Always keep your knee slightly bent. Do not let the knee buckle inwards. Keep your pelvis horizontal and do not let it tilt to the side. Keep your weight on the ball of the foot or lift your heel from the ground.

25. Jumping an 8-point star.

Materials: - 8 cones

Action: Mark an 8-point star with cones. The size of the star depends on the length of the players. Stand in the middle of the star and balance on your non-dominant leg. Jump to a point of the star and back to the center again. Make sure you jump to all cones. Repeat the exercise on your dominant leg.

Important: Always keep your knee slightly bent. Do not let the knee buckle inwards.

Exercises to perform on the field with a large group of players:

26. Reactively changing direction.

Materials: - 3 cones

Action: The three cones are positioned in a T-shape. Two players jog side by side from the middle cone to the centre of the other two cones. By means of a signal (left or right), the coach indicates whether the players should sprint to the left or right cone. Subsequently, the farthest player should try to tap the nearest player, before reaching the cone. When the nearest player is tapped before reaching the cone, roles are changed in the direction of the other cone, until one of the players has reached his cone.

27. Aerial duel.

Materials: *- 3 cones*

Action: The three cones are positioned in a T-shape. Two players jog side by side from the middle cone to the center of the other two cones. When the coach gives a signal, both players perform an aerial shoulder to shoulder duel and subsequently sprint as fast as possible to the cone on their own side.

28. Left-right jumping.

Materials: *none*

Action: Stand with your feet shoulder width apart, with a line in between your feet. Slightly bend your knees and hip. Jump with both your feet approximately 30 cm to the left, while at the same time making a quarter turn leftwards, so that you are facing in the direction of the jump. Then jump back to the starting position and perform the same jump rightwards and back to the starting position. This is one cycle. Repeat this cycle five times, rest for 10-20 s and then repeat once more. Perform the exercise as fast as possible. Land softly on the balls of both feet with knees slightly bent.

Important: A soft landing and quick take-off are more important than the height of the jump. Do not let your knees buckle inwards.

29. Zigzag shuffle.

Materials: *- 6 cones*

Action: Make a zigzag course with 6 marks set at 10 x 20 m. Stand at the start of the zigzag course, legs shoulder width apart. Bend the knees and hips so the upper body leans substantially forward. One shoulder points in the direction of movement. Shuffle sideways to the first mark, turn so that the other shoulder points to the next mark and complete the zigzag course as fast as possible. Always take-off and land on the balls of your feet. Complete the course twice.

Important: Always keep your upper body leaned forward with the back straight. Keep your knees slightly bent, do not let them buckle inwards.

30. Bounding.

Materials: *- 2 cones*

Action: Stand on your take-off leg with the upper body upright. The arm of the same side is in front of the body. When viewed from the front, hip, knee and foot of the take-off leg should be in a straight line. Spring as high and far as possible off the supporting leg. Bring the knee of the trailing leg up as high as possible and the opposite arm bent in front of the body when bounding. Land softly on the ball of the foot with a slightly bent knee. You now

landed on the trailing leg. Try to maintain balance and repeat the bounding action on this leg. Cover 30 m twice.
Important: Do not let your knee buckle inwards during take-off and landing.

31. Somersaulting.
Materials: *- 2 cones*
Action: Somersault over a line and alternately rise up on your left and right leg, while maintaining balance. Cover 20 m twice.

32. Follow the leader.
Materials: *- stopwatch + 4 cones*
Action: Mark out an area of 20 x 20 m. Pair up with a teammate and run randomly within the area. One player follows the leader, staying within a distance of 2 m. The leader maintains the same speed throughout the exercise, but constantly changes direction. After 20 s, roles are changed.

6. Summary & General Discussion

Aims

The first aim of the present thesis was to have a closer look at the concept of core stability from a scientific perspective. An attempt was made to provide a universally usable definition of core stability, to stimulate that future discussions regarding the subject matter concern one and the same concept. The second aim was to present valid and reliable measurement methods to quantify core stability, based on the definition formulated. The third aim was to study the effect of a soccer specific neuromuscular training program (NMTP) on core stability in elite youth soccer players, using these measurement tools. Besides, as a secondary aim, the effect of the training program on standing balance and agility as performance measures and on injury occurrence was investigated.

With respect to the first aim, in chapter 2 an overview was given of the existing literature regarding several issues related to core stability. A first step towards a valid measurement method was made in chapter 3, where core muscle response times and sitting balance performance were compared between soccer players and nonplayers. On the basis of these findings, measurement methods were further adapted and refined. In chapter 4, the construct validity of these newly developed methods was described and their reliability was investigated in a group of 30 university students. In chapter 5, the measurement methods were used in a group of 90 elite youth soccer athletes to study the effect of a soccer specific NMTP on improving core stability. Furthermore, this study also tried to find a link between core stability on the one hand and standing balance and agility as performance measures and injury occurrence on the other hand.

Summary of Main Findings

With respect to defining the concept of core stability, chapter 2 first looked at the separate notions of core and stability, to eventually combine them into one usable definition of core stability. The body's core is part of the human trunk. The trunk roughly exists of three parts: the pelvis, the lumbar vertebral column and the thoracic vertebrae with all their respective surrounding tissues. From an anatomical point of view, the core is defined as the lumbar vertebral column with all its surrounding tissues, both passive (tendons and ligaments) and active (muscles). As such, the core constitutes a connection between the hips and the thoracic part of the trunk. Chapter 2 showed that there is no single universally accepted definition of core stability. For the purpose of the present thesis, we have looked at the concept of stability from a biomechanical perspective.

Chapter 4 elaborated on this, referring to a study by Reeves et al.[25] They indicated that a certain system (for example the human body) is either stable or not: balance is maintained or balance is lost. Stabilizing the human trunk is essential in maintaining upright posture, especially when encountering internal or (expected or unexpected) external balance perturbations. Chapter 2 showed that stabilizing the core is a dynamic process of maintaining balance, in which the core muscles adequately react on sudden perturbations. For the purpose of the present thesis, an adapted version of the definition by Zazulak et al.[37] was used. Core stability was defined as the ability of the neuromusculoskeletal system to control trunk position in labile situations or in response to sudden balance perturbations. Chapter 2 showed that neuromuscular control of the core muscles is most important in controlling trunk position. All core muscles work together in providing stability, but the larger, more superficial muscles play a key stabilizing role in correctly positioning the upper body.[12] The neuromuscular system anticipates by means of pre-programmed muscle activations on expected balance perturbations. In the case of unexpected perturbations, the trunk is stabilized through direction specific reflexive muscle contractions. In many sports, including soccer, exerting external forces while attempting to maintain dynamic balance forms the base of a successful performance. The art is to enhance mobility, while at the same time preserving sufficient stability.

All the literature findings described in chapter 2 formed a base for the development of a valid core stability measurement method. In chapter 3, a first step in this respect was made by investigating whether 10 high amateur-level soccer players had a better reflexive core neuromuscular control than 11 less active nonplayers. While sitting on a balance seat, subjects were presented with sudden trunk loading in the frontal and sagittal plane to study core muscle reflex latencies and kinematic responses of the balance seat. Soccer players showed shorter reflex latencies compared to nonplayers for the rectus abdominis, erector spinae and externus obliquus muscles in response to sagittal plane perturbations. These shorter reflex latencies went along with faster and greater seat movement in response to sudden trunk loading, with weak to moderate correlations between the two measures. The weak to moderate relationship between core muscle onset times and seat kinematic data might be explained by the core muscle onset giving an indication of the speed of response onset, whereas the mechanical measures are telling more about the quality of the responses. The soccer players might have relied more on better-developed feed-forward processes for their responses, with concurrent proprioceptive feedback being less important. This stronger reliance on feed-forward processes by means of pre-programmed responses may have resulted in a higher response velocity and hence greater seat movement.

On the basis of the findings described in chapter 3, new measurement methods were developed as described in chapter 4. In this chapter, the graduated sitting balance test and seated perturbation test were introduced as clinical tests to make the core stability concept measurable in a valid and objective way. Furthermore, test-retest reliability of these measurement methods, together with an adapted version of the narrow ridge balance test as developed by Curtze et al.,[7] was investigated in 30 university students. The idea behind the graduated sitting balance test was based on the notion by Reeves et al.[25] that a system is either stable or not. In comparison with Tanaka et al.,[30] we introduced a new way to indicate a threshold of stability for evaluating the level of core stability. The strength of this approach is the fact that the transition between stable and unstable behaviour is identified and quantified. To overcome the problem encountered in chapter 3 of either looking at the speed of responses to sudden perturbations by means of electromyography, or looking at the quality of the responses through kinematic data, the seated perturbation test was developed which provided one single performance measure reflecting both the accuracy and speed of subjects responses to sudden perturbations. The principle behind this measure was based on work by Marshall et al.,[15] who introduced time to stabilization as a performance measure to investigate lower limb function. Chapter 4 showed that test-retest reliability of the three tests investigated was moderate to substantial, with some measures showing almost perfect reliability. To be noticed is the systematic bias found between the two test sessions, indicating a learning effect. Correlations between the results of the different tests indicated that adequate reactive neuromuscular trunk control may play a role in stabilizing both standing and seated posture in the frontal plane.

The measurement methods described in chapter 4 were used in chapter 5 to investigate the effect of a soccer-specific NMTP on improving core stability in 90 elite male youth soccer players. Besides, the effect of the program on whole-body stability and agility as indicators of performance and on injury occurrence was evaluated. Although positive trends in the data indicated that the NMTP had a positive effect on reactive core stabilizing control, standing balance capacity and slalom sprint performance, no significant differences in improvement were found for the stability and agility test results between the intervention and control group. In this respect it has to be noticed that the lack of significance found does not directly imply that the effect of the NMTP is irrelevant. The positive trends found for the intervention group may be very important for a successful sports career in the present group of highly trained elite youth soccer players. The comparable positive trends in the data for both standing balance and slalom sprint performance might indicate that increased one-leg stability might carry over to the stance phase of running, thereby improving agility performance. With respect to the effect of the

NMTP on injury occurrence, chapter 5 showed no significant differences in injury incidence or severity between the intervention and control group. Furthermore, the stability test results could not be used as predictive values for injury occurrence. In this respect it has to be noticed that the relatively small amount of subjects and the inclusion of only new non-contact time-loss injuries resulted in a low number of injuries sustained during the intervention period.

Research Limitations

In the measurement methods used in the present thesis to quantify core stability, subjects adopted a seated position. Although the seated posture is not a functional athletic position, this posture was chosen to exclude other potential neuromuscular response strategies by the lower extremities. The question should be raised whether performance in these tests accurately reflects the subcortical neuromuscular core control that is trained in a standing position during soccer activities. Although the instruments give an indication of an individual's level of core stability, a true understanding of the stabilizing role of the body's core during whole-body movements while playing sports requires sport specific testing. The challenge in this respect is to find a practical way to isolate core stability from the stabilizing activities of the lower extremities, while testing in an upright, sport specific posture. While playing soccer, the core operates in a world where peripheral contact with the ground is important. Forces affecting the body from foot contact up the kinetic chain are clearly important, but the same applies to centre down forces. Another limitation in the present thesis is the fact that, in the measurement instruments used in the present thesis, stability was only challenged in the frontal and sagittal plane, not taking into account rotational forces acting in the lateral plane. These forces may have a huge influence on the stabilizing capacity of the core in a sport like soccer, when for example kicking a ball. An interesting recent finding with respect to the influence of stability in soccer is the high and significant correlations found by Chew-Bullock et al.[4] between one-legged balance ability and kicking accuracy.

Despite the limitations mentioned above, the tests presented in chapter 4 to quantify core stability were shown to be more valid and reliable than previous attempts trying to measure core stability by observing and rating the performance on static exercises.[14,35] The advantages of the narrow ridge balance test and the graduated sitting balance test described in chapter 4 are their simplicity and low costs, which make them useful instruments to screen the balance capacity of a large number of subjects in a clinical setting. Chapter 4 also showed some shortcomings of these measurement instruments. In chapter 5 it was stated that the test battery used may not have detected all potential improvements in stability in the elite youth soccer athletes due to a lack of sensitivity. To increase the reliability and responsiveness of the narrow ridge balance test and to eliminate the ceiling effect found in the graduated sitting balance test (chapter 4), these tests can easily be extended with extra ridges or balance boards, thereby creating extra levels of test difficulty leading to an increase in between-subject variation in the test results. Furthermore, in chapter 4 a learning effect was shown in subjects performing the stability tests twice with one week in between. A way to overcome the problem of such a learning effect is to present subjects with one or more pre-test familiarization trials.

The intention of the NMTP described in chapter 5 was to use soccer-specific exercises, thereby making the program functional enough to translate into improvements in sports performance. This intention lead to balance exercises with body postures resembling postures adopted during regular soccer practice exercises, whereby the training content of the intervention and control group became more equal. This might have been disadvantageous in finding a significant effect of the program on the stability parameters tested. Reasoning from the principle of specificity, most performance improvement might have been expected on the narrow ridge balance test, but this was not shown by the results in chapter 5. With respect to the volume of the NMTP exercises performed, the question could be raised what the additional effect will be of twice a week 15 min soccer specific neuromuscular training in elite youth soccer athletes who train on average six hours a week. Based on the marginal comments with respect to the contents and volume of the NMTP as postulated above, chapter 5 concluded with the remark that the positive trends found for the stability and agility parameters in the intervention group may be very important for a successful soccer career. Increasing the volume of the exercises, for example by integrating the exercises in every training session's warm-up, may amplify these positive trends.

Future Perspectives

The research presented in this thesis mainly built on the literature finding described in chapter 2 that until now there is no valid, reliable and sufficiently sensitive measurement protocol to quantify core stability. Without such a measure it is impossible to investigate a relationship between core stability on the one hand and physical performance and injury occurrence on the other. Furthermore, it is impossible to study the effect of a NMTP on the capacity to stabilize the trunk.

In chapter 3 a first attempt was made in quantifying reactive core stabilizing control by means of kinematic data. Because in this chapter only weak correlations were found between core muscle reflex latencies and mechanical measures of the balance seat in response to sudden trunk perturbation, it would be interesting for future research to offer subjects a similar perturbation test during which kinematic data of the upper trunk –

instead of the seat – are obtained and compared with the core muscle reflex latencies. A clearer association between these two measures is to be expected because of the more direct relationship between core muscle reflexes and trunk movement compared with balance seat movement. On the basis of model simulations, Reeves et al.[24] already showed that longer reflex delays produce more balance instability, increased trunk displacement and greater trunk moments. But further research is recommended to confirm the results of such model simulations with findings obtained testing subjects in real-life situations. Furthermore, investigation is required to look for the cause of delayed muscle responses and to see whether shorter muscle response times actually result in a reduced risk of injury. Because the body's core is often referred to as the foundation from which all limb movements occur,[1] in a sport like soccer it would be interesting for future research to look at the relationship between the activation speed of the trunk muscles and the speed of activation of the hip musculature.

With respect to injury incidence, chapter 5 indicated that the relatively small amount of subjects and the inclusion of only new non-contact time-loss injuries resulted in a low number of injuries sustained during the intervention period. For future research it is recommended to follow athletes through multiple sport seasons, by making use of prospective longitudinal studies, to further investigate the relationship between core stability and injury risk. Though the present thesis did not demonstrate this relationship, previous research found an association between a decreased stability (impaired postural control, delayed core muscle reflex responses and abnormal muscle recruitment patterns) and a higher risk of sustaining a low back or knee injury.[5,6,23,32,37,38] However, the results with respect to knee injury were mainly found in female athletes. Furthermore, previous studies investigating the injury preventive effect of neuromuscular training programs mainly found positive results in female and low skill playing level male athletes.[2,11,21,29,36] Based on this, it is likely that female and amateur level soccer players would benefit more from a soccer-specific NMTP and therefore future research in this respect is recommended.

Theoretical Considerations

Because postural trunk stability is viewed from different professional disciplines, the concepts of core stability and spine stability are frequently used interchangeably, which creates confusion about the importance of different groups of core muscles. In chapter 2 it was demonstrated that mainly the larger, more superficial core muscles provide core stability (controlling trunk position).[12] A prerequisite for this postural stability is a secured underlying spine stability. This is the ability to resist translation and rotation of the spinal vertebrae.[20] In a clinical situation, the term stability is often used when a joint is sufficiently stiff to withstand stability-provoking actions. This spine stability is mainly provided by the smaller, deeper laying core muscles which are automatically active during regulation of posture and movement. Obscurity is mainly caused by the fact that some authors define core stability as stabilizing *of* the core (the lumbar vertebral column),[14,16] while others look at core stability as stabilizing the trunk *from* the core; controlling the position and motion of the trunk as a whole over the pelvis.[13,37,38] The second point of view is applied in the present thesis. For future work it is highly recommended to make a clear distinction between the concepts of spine stability and core stability.

With respect to measuring core stability, the present thesis adds to the debate whether measures obtained with posturography give a useful indication of stability. There is continuous debate about optimal selection of discriminative sway parameters, like for example the discussion whether more postural sway during a balance task is associated with poorer balance performance and less stability. It is commonly assumed that increased variability indicates greater instability, though results in this respect are inconsistent.[8,9,18] The target for the neuromuscular system in maintaining balance is to keep the so-called extrapolated centre of mass position within the base of support,[10] not to minimize the amount of sway. In this respect, chapter 3 showed that soccer players moved back to equilibrium with a higher maximum seat angular velocity compared to the nonplayers. Chapter 3 illustrated that more sway is not necessarily associated with less stability. This is in accordance with a study by Van Dieën et al.,[33] who found that lower sway velocity during a sitting balance task was associated with less stability, indicated by a loss of balance. These theoretical considerations have huge implications with respect to the interpretation of outcome measures currently used to quantify core stability.

Globally considered, three determinants can be distinguished which together determine core stability: core muscular endurance, strength of the core muscles and the power the core muscles can generate (Figure 1). However, as seen in chapter 2, the central component is the neuromuscular control of the core musculature. Without adequate control, optimal conditioning of the three determinants will not have the intended effect on performance optimization and/or injury prevention.

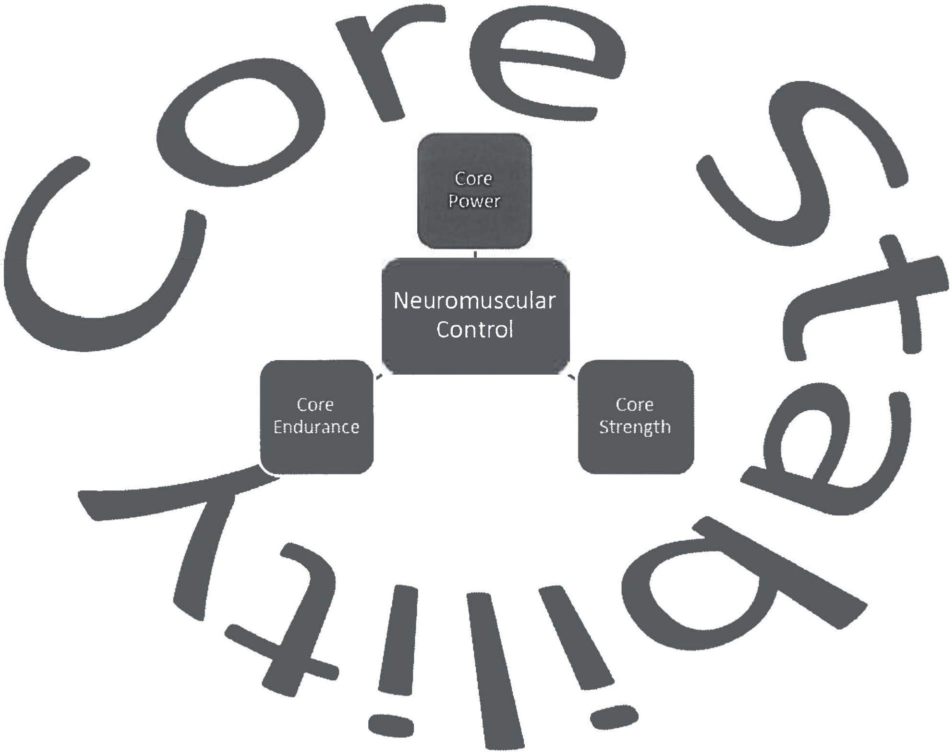

Figure 1. The three determinants of core stability with neuromuscular control as the central component.

Practical Implications & Concluding Remarks

Depending on the training situation (performance optimization, injury prevention or rehabilitation) and kind of sport, the training focus should be on one or more of the three determinants. A difference can be made between sports in which an optimal, relatively static position of the trunk should be maintained during a shorter or longer period of time (eg. running, cycling or ice skating) and sports in which the position of the trunk with respect to the lower extremities is continuously changing (eg. ball team sports). Within the latter, more dynamic sports, the focus can also be on one or the other determinant. For example, compare a sport like korfball, in which physical contact is not allowed, with a sport like rugby, in which there is made a much greater appeal to the components of core strength and power. And even within a certain kind of sport a distinction can be made between the required physical conditions concerning different playing positions. For example in soccer, the core stability focus for a skilful winger is different compared to that of a robust central defender.

Looking into the present scientific literature regarding methods to measure and train core stability, a lack of clarity is created by authors using the notions of stability, endurance, strength and power interchangeably. Several studies tried to determine the effect of improvements in core endurance on performance aspects of strength and power, while these are different components.[17,19,28,31] To effectively investigate the effect of core training on performance, it is necessary to link the relevant determinants of core stability to the corresponding performance components. The fact that there is so little known about the relationship between core stability and sports performance, as shown in chapter 2, is mainly caused by a lack of scientific studies which try to directly correlate both aspects. So it is of utmost importance to actually measure what is intended to train. A good example in the case of measuring core stability is a study by Van Dieën et al.,[34] who investigated the influence of fatigue on core stability in top level gymnasts by actually measuring stability through an unstable sitting balance test with and without balance perturbations. In a comparable way, this thesis tried to measure core stability by quantifying core neuromuscular control.

The current trend with respect to core training is the use of static exercises, generally performed in a lying position with the emphasis on isometric muscle contractions. Besides, it is a trend to perform exercises assuming different postures (lying, sitting, standing) using unstable surfaces, like for example Swiss balls or wobble boards. Research on the effect of these exercises on core properties and sports performance has shown varying results.[28] A certain kind of instability training, so-called sling exercise training, in which instability is created by placing certain body parts in a carrying strap while exercising, is found to have a positive effect on maximal throwing, kicking and striking velocity in respectively handball, soccer and golf.[22,26,27] The positive outcomes may have been a result of the postures, movements and load being more sport specific compared to other forms of instability training. For performance improvement it is important that the training of core endurance, strength and power is integrated in exercises in which the neuromuscular system is triggered in a sport specific way. The contents of the training intervention (chapter 5) was tuned to this, taking into account the principle of specificity: the postures and movements in the exercises resembled as much as possible the soccer specific postures and movements. Instability was mainly created by performing sport specific exercises unilaterally. In soccer, many activities are performed unilaterally. Research revealed that the core musculature is more active when exercising on one leg, in which stability of the trunk is challenged in different directions.[3]

All together it is recommended to pay attention to core stability in the training programs of athletes. From a scientific perspective, core training should be presented in different ways, depending on the kind of sport, phase of training and health status of the athlete. There is an important task for physical coaches and physiotherapists to select the right core exercises, based on the situation and task specific demands placed on the core musculature in a certain setting. It is important to optimally stress the right determinants (core endurance, strength and power) of core stability. The training program presented in the present thesis mainly comprised of whole-body balance exercises, focusing on control. These exercises can easily be integrated in every training session's warm-up. To specifically improve a certain determinant of core stability, the core musculature should be trained more isolated using exercises in which relatively stable postures are adopted. To translate the acquired training result into performance enhancement in a certain kind of sport, it is vital to perform exercises in which sport specific body postures and movements are adopted. In a sport like soccer, the ability to maintain or resume upright body posture can be heavily challenged. Here the keyword 'neuromuscular control' comes into play. The core musculature can be optimally trained in the areas of muscular endurance, strength and power. However, when the right muscles are not being activated at the right time, for the right duration and when they are not producing the right amount of force, instability can still arise and consequently an injury-free performance at top level will not be achieved.

Though the common view exists that a stable core is important with respect to performance optimization and injury prevention, further research is needed to scientifically substantiate this image. The present thesis was an attempt into this direction. On the basis of a carefully chosen definition of core stability, valid measurement methods were developed to eventually investigate the effect of functional, soccer specific exercises on the ability to stabilize the trunk. Further research in this area will eventually contribute to the development of effective training programs, intending to optimize performance and minimize injury incidence.

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Samenvatting

Het eerste doel van dit proefschrift was het nader belichten van het core stability concept vanuit een wetenschappelijk perspectief. Er is een poging gedaan om een universeel bruikbare definitie van core stability aan te reiken, om hiermee te stimuleren dat toekomstige discussies rondom dit thema over één en hetzelfde concept gaan. Een tweede doel was om, gebaseerd op de geformuleerde definitie, valide en betrouwbare meetmethoden te presenteren waarmee core stability kan worden gekwantificeerd. Het derde doel was om het effect van een voetbal specifiek neuromusculair trainingsprogramma op de core stability bij jonge profvoetballers te onderzoeken, gebruik makend van de ontwikkelde meetmethoden. Daarnaast was een secundair doel het onderzoeken van het effect van het trainingsprogramma op stabalans en wendbaarheid als prestatiematen en op het voorkomen van blessures.

Met betrekking tot het eerste doel gaf hoofdstuk 2 een overzicht van de bestaande literatuur aangaande core stability. Als het gaat om het definiëren van het core stability concept, is in hoofdstuk 2 eerst gekeken naar de afzonderlijke begrippen core en stability, om ze uiteindelijk te combineren in één bruikbare definitie van core stability. Vanuit anatomisch oogpunt is de core gedefinieerd als de lumbale wervelkolom met alle omliggende structuren, zowel passieve (pezen en ligamenten) als actieve (spieren). Hoofdstuk 2 liet zien dat er geen universeel geaccepteerde definitie van core stability is. Voor het huidige proefschrift is core stability gedefinieerd als de vaardigheid van het neuromusculoskeletale systeem om vanuit de core de positie van de romp te controleren in labiele situaties of in reactie op plotselinge balansverstoringen. In veel sporten, waaronder voetbal, vormt het leveren van externe krachten, terwijl gelijktijdig de dynamische balans moet worden gehandhaafd, de basis voor een succesvolle prestatie.

Alle literatuurbevindingen, beschreven in hoofdstuk 2, vormden de basis voor de ontwikkeling van een valide core stability meetmethode. In hoofdstuk 3 is hiermee een eerste stap gemaakt door te onderzoeken of 10 amateurvoetballers, uitkomend op een hoog niveau, een betere reflexieve neuromusculaire controle rondom hun core hadden dan 11 minder actieve niet-voetballers. Zittend op een balansstoel werd de balans van de proefpersonen in voor-/achterwaartse en zijwaartse richting plotseling verstoord, om vervolgens spierreactietijden en bewegingsdata van de balansstoel te kunnen onderzoeken. De voetballers lieten kortere spierreactietijden zien in vergelijking met de niet-voetballers in reactie op voor-/achterwaartse balansverstoringen. Deze kortere spierreactietijden gingen gepaard met snellere en grotere bewegingsuitslagen van de balansstoel, waarbij correlaties tussen beide maten matig waren. Een verklaring voor de matige correlaties zou kunnen zijn dat de spierreactietijden een indicatie geven van de snelheid waarmee de reactie wordt geïnitieerd, terwijl de bewegingsdata meer vertellen over de kwaliteit van de respons.

Op basis van de bevindingen in hoofdstuk 3 zijn vervolgens de meetmethoden verder aangepast en verfijnd. In hoofdstuk 4 is de construct validiteit van deze nieuw ontwikkelde meetmethoden (de 'graduated sitting balance test' en de 'seated perturbation test') beschreven en is de test-hertest betrouwbaarheid van deze meetmethoden, samen met een aangepaste versie van de 'narrow ridge balance test', onderzocht in een groep van 30 studenten. Het idee achter de 'graduated sitting balance test' is de notie dat een systeem ofwel stabiel is, ofwel instabiel. Met deze test werd een drempelwaarde voor het niveau van core stability geïntroduceerd. De kracht van deze benadering is dat de transitie van stabiliteit naar instabiliteit wordt bepaald en gekwantificeerd. De 'seated perturbation test' reflecteerde met één enkele prestatiemaat (tijd tot stabilisatie) zowel de nauwkeurigheid als de snelheid van de reacties van proefpersonen op onverwachte balansverstoringen. Hoofdstuk 4 liet zien dat de test-hertest betrouwbaarheid van de 3 onderzochte testen matig tot aanzienlijk was, waarbij sommige maten een zeer hoge betrouwbaarheid lieten zien. Wel was er sprake van een leereffect. Correlaties tussen de resultaten van de verschillende testen lieten zien dat adequate reactieve neuromusculaire controle vanuit de core een rol zou kunnen spelen in de zijwaartse stabiliteit tijdens staan en zitten.

De in hoofdstuk 4 beschreven meetmethoden zijn in hoofdstuk 5 gebruikt om het effect van een voetbal specifiek neuromusculair trainingsprogramma op het verbeteren van core stability te onderzoeken in een populatie van 90 jeugdige profvoetballers. Daarnaast werd het effect van het trainingsprogramma op stabalans en wendbaarheid als prestatiematen en op het voorkomen van blessures onderzocht. Hoewel positieve trends in de data aanduidden dat het programma een positief effect had op reactieve balanscontrole vanuit de core, stabalans vaardigheid en slalom sprint prestatie, werden er geen significante verschillen in verbetering gevonden tussen de interventie- en controlegroep. Hierbij moet worden opgemerkt dat het ontbreken van significantie niet impliceert dat het effect van het trainingsprogramma irrelevant is. De positieve trends, gevonden voor de interventiegroep, zouden heel belangrijk kunnen zijn voor een succesvolle sportcarrière in de onderzochte populatie van goed getrainde jeugdige profvoetballers. Met betrekking tot het effect van het trainingsprogramma op blessure incidentie liet hoofdstuk 5 geen significante verschillen zien tussen de interventie- en controlegroep. Bovendien konden de testresultaten niet worden gebruikt als voorspellende waarden voor het oplopen van blessures. Hierbij moet worden opgemerkt dat het relatief kleine aantal proefpersonen en de inclusie van enkel nieuwe niet-contact blessures resulteerde in een laag aantal opgelopen blessures tijdens de interventieperiode.

Hoewel de algemene opvatting heerst dat een stabiele core van belang is met betrekking tot het optimaliseren van prestaties en het voorkomen van blessures, is verder onderzoek nodig om dit beeld wetenschappelijk te onderbouwen. Het huidige proefschrift was een poging in deze richting. Op basis van een zorgvuldig gekozen definitie van core stability werden valide meetmethoden ontwikkeld, waarmee uiteindelijk het effect werd onderzocht van functionele, voetbal specifieke oefeningen op de vaardigheid om de romp te stabiliseren. Verder onderzoek op dit gebied zal uiteindelijk bijdragen aan de ontwikkeling van effectieve trainingsprogramma's, welke beogen prestaties te optimaliseren en het aantal blessures te minimaliseren.

List of Publications

Peer-reviewed International Journals

- Borghuis AJ, Hof AL, Lemmink KAPM. The Importance of Sensory-Motor Control in Providing Core Stability: Implications for Measurement and Training. *Sports Med.* 2008;38(11):893-916.
- Borghuis AJ, Lemmink KAPM, Hof AL. Core Muscle Response Times and Postural Reactions in Soccer Players and Nonplayers. *Med Sci Sports Exerc.* 2011;43(1):108-114.

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- Borghuis AJ. Het Belang van Rompstabiliteit. Physios. 2011;3(2):4-11.
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Book Chapter

- Borghuis AJ. Wie niet sterk is, moet stabiel zijn. In: Bongers R, Caljouw S, Hartman E, Den Otter R (Eds.). Smart Movements. 25 jaar Bewegingswetenschappen Groningen. Interfacultair Centrum voor Bewegingswetenschappen, Universitair Medisch Centrum Groningen, Rijksuniversiteit Groningen. 2010:108-111.

Conference Contributions

- Borghuis AJ, Hof AL, Lemmink KAPM. Core Muscle Response Times and Balance Performance in Soccer Players and Non-Players. Book of Abstracts. 16th edition of the International Student Congress of Medical Sciences. Groningen, 2009.
- Borghuis AJ, Lemmink KAPM, Hof AL, Visscher C. The Effect of a Soccer-Specific Neuromuscular Training Program on Stability, Agility and Injury Occurrence in Elite Youth Soccer Players. Book of Abstracts. 16th Annual Congress of the European College of Sport Science. Liverpool, 2011:298.
- Borghuis AJ, Lemmink KAPM, Hof AL. Reliability of Three Clinical Tests Measuring Core and Whole-Body Stability. Book of Abstracts. 16th Annual Congress of the European College of Sport Science. Liverpool, 2011:625.

Invited Talks

- Borghuis AJ, Hof AL, Lemmink KAPM. The Importance of Sensory-Motor Control in Providing Core Stability: Implications for Measurement and Training. 8th Groningen Sports Medicine Symposium. Groningen, 2010.
- Borghuis AJ. Core Stability en de Enkel. NVFS Jaarcongres Fysiotherapie. Utrecht, 2010.
- Borghuis AJ. De Reflexieve Component van Rompstabiliteit bij Jeugdige Profvoetballers. Wetenschappelijke bijeenkomst van de Vereniging voor Sportgeneeskunde. Bilthoven, 2012.

Curriculum Vitae

Arend Jan Borghuis is geboren op 12 september 1985 te Kampen. Hij studeerde van 2003 tot 2011 Bewegingswetenschappen aan de Rijksuniversiteit Groningen waar hij tijdens de master vakken volgde binnen de afstudeerrichtingen sport en revalidatie. Tijdens de master schreef hij een review artikel over het belang van sensomotorische controle voor het handhaven van rompstabiliteit. De master thesis volgend op het review artikel handelde over rompspierreactietijden en balansvaardigheden bij voetballers en niet-voetballers.

Beide artikelen vormden in 2009 de opstap naar een MD/PhD-traject binnen het Interfacultair Centrum voor Bewegingswetenschappen, een traject mede mogelijk gemaakt door de Junior Scientific Masterclass. In samenwerking met de instrumentmakerij binnen het UMCG en de ICT ontwikkelaars binnen Bewegingswetenschappen werkte hij aan de ontwikkeling van zitbalanstaken om bepaalde aspecten van rompstabiliteit in kaart te kunnen brengen. In een samenwerkingsverband met de FC Twente Voetbalacademie werden de ontwikkelde meetmethoden vervolgens ingezet om de stabiliteit van jeugdige profvoetballers en de trainbaarheid van deze stabiliteit te onderzoeken. Dit promotie-onderzoek rondde hij in 2013 af.

Van september 2011 tot februari 2013 werkte Jan voor Fysiogym Twente, waar hij betrokken was bij de revalidatie van patiënten, het testen en monitoren van CVA-patiënten, de voetbal specifieke veldrevalidatie van geblesseerde spelers en het fysiek testen en monitoren van spelers binnen de FC Twente Voetbalacademie. Tevens was en is hij nauw betrokken bij de ontwikkeling van TwenteLab, een initiatief, uitgaande van een consortium waarin onder andere Fysiogym Twente en FC Twente deelnemen, om innovaties binnen de topsport te implementeren, waarbij op langere termijn ook de breedtesport en de reguliere zorg moeten profiteren van de nieuwe ontwikkelingen.

Sinds maart 2013 is Jan als inspanningsfysioloog / fysiek trainer in dienst van FC Twente. In deze functie is hij door de hele club heen betrokken bij de ontwikkeling en uitvoering van trainingsprogramma's, het fysiek testen en monitoren van de belasting / belastbaarheid, de ontwikkeling van blessurepreventieve en revalidatierichtlijnen en het werken aan fysiek beleid met daarin ruimte voor innovatie.

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YOU CAN DO IT!

zet'm op Jan
met die ..... promotie.

Mirri