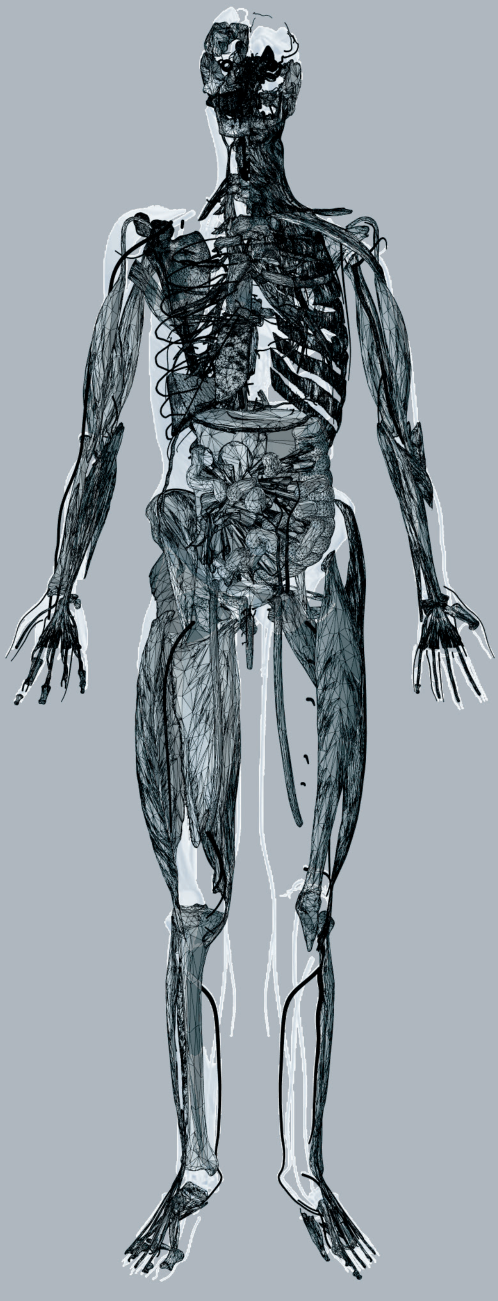
Core stability

Clinical assessment tools and the role of core stability in the development of lower extremity injuries

Cedric De Blaiser



ISBN
9789082806410

Cover Art
Dhr. Frederik Vanhoutte

Design/lay-out
Promotie In Zicht, Arnhem

Print
University Press

Core stability:

Clinical assessment tools and the role of core stability in the development of lower extremity injuries

Cedric De Blaiser

Promotor:
Prof. Dr. Philip Roosen
Co-Promotor:
Dr. Roel De Ridder

Thesis submitted to fulfill the requirements
for the degree of Doctor in Health Sciences
Ghent University, 2018

Department of Rehabilitation Sciences
Faculty of Medicine and Health Sciences

GHENT UNIVERSITY

FACULTY OF MEDICINE AND HEALTH SCIENCES

Promotor

Prof. Dr. Philip Roosen	Ghent University, Ghent, Belgium

Co-Promotor

Dr. Roel De Ridder	Ghent University, Ghent, Belgium

Process Supervisory Board

Prof. Dr. Tine Willems	Ghent University, Ghent, Belgium
Prof. Dr. Lieven Danneels	Ghent University, Ghent, Belgium
Prof. Dr. Luc Vanden Bossche	Ghent University Hospital, Ghent, Belgium

Examination Board

Prof. Dr. Patrick Calders *(chairman)*	Ghent University, Ghent, Belgium
Prof. Dr. Christophe Demoulin	University of Liège, Liège, Belgium
Prof. Dr. Nathalie Roussel	Antwerp University, Antwerp, Belgium
Dr. Veerle Stevens	Ghent University, Ghent, Belgium
Dr. Lennert Goossens	Ghent University, Ghent, Belgium
Prof. Dr. Ruth Verrelst	Ghent University, Ghent, Belgium

‘Sometimes it’s the journey that teaches you a lot about your destination.’

Aubrey Drake Graham

Table of contents

General introduction		9
	1. Introduction	11
	2. Core stability	11
	3. Background and aims	24
Chapter 1	**An overview of current literature on core stability and the association with lower extremity injuries**	33
	Part I: Is core stability a risk factor for lower extremity injuries in an athletic population ? A systematic review.	35
Chapter 2	**Reliability and validity of clinical assessment tools to evaluate core stability**	57
	Part I: Evaluating abdominal core muscle fatigue: assessment of the validity and reliability of the prone bridging test.	59
	Part II: Reliability and validity of trunk flexor and trunk extensor strength measurements using handheld dynamometry in a healthy athletic population.	77
	Part III: Reliability of two functional clinical tests to evaluate trunk and lumbopelvic neuromuscular control and proprioception in a healthy population.	93
Chapter 3	**The role of core stability in the development of lower extremity injuries**	111
	Part I: Impaired core stability as a risk factor for the development of lower extremity overuse injuries: a prospective cohort study.	113
General discussion		135
	1. Summary	137
	2. Main discussion	138
	3. Clinical implications	150
	4. Strengths and limitations	158
	5. Future perspectives	161
	6. General conclusion	163
Nederlandse samenvatting		173
List of abbreviations		175
Acknowledgements | dankwoord		177
Curriculum vitae		179

GENERAL INTRODUCTION

1 Introduction

Impaired core stability has been hypothesized to contribute to the development of lower extremity injuries (**LEI**). However, there is only limited or contradictory evidence to support this hypothesis, and further research to investigate this relationship is needed. Therefore, the general aim of this dissertation is to provide an insight into the role of core stability in the development of LEI. The general introduction of this dissertation will provide a deeper look into the concept of core stability with regards to the definition, anatomy and functioning. The current literature will be discussed to procure a definition of core stability which will be used throughout the dissertation. Next, assessment methods for core stability will be discussed with regard to the existing measurement methods and their reliability and validity. Furthermore, the relationship between core stability, lower extremity functioning and lower extremity (overuse) injury (**LEOI**) will be explored. Finally, the background and different aims of this dissertation will be explained more in detail at the end of the general introduction.

2 Core stability

2.1 An overview of the concept

Since the use of core stability and core stability training has been widely accepted in the area of clinical rehabilitation, sports medicine and athletic training, [1,85,107] it is reasonable to expect that the definition and the components, which contribute to core stability have been well established. However, many synonyms and descriptions exist in current literature to address this concept. Furthermore, various anatomical structures and working mechanisms for this concept are used interdependently in scientific research. In an attempt to reach expert consensus on the concept of core stability, a Delphi-Study was set up by Majewski-Schrage et al.[64] In their study, core stability was defined as the ability to achieve and sustain control of the trunk region at rest and during precise movement. Furthermore, different trunk muscles were agreed upon as essential for stability of the core and, neuromuscular control was suggested as the main factor for optimal functioning of these muscles to provide core stability. However, set against present literature and own expertise, the flaws in this operational definition are exposed. Only including the abdominal and lumbar musculature as anatomical aspects which contribute to core stability and, proposing neuromuscular control as the only component to regulate core stability can be considered as being too limited and uncomprehensive. As such, the core stability definition and components as described by Majewski-Schrage et al.[64] was merely used as a starting point for further exploration. The aforementioned definition was used as a starting point and the prominent current literature was consulted alongside the expertise and experience of the research group, involved in the realization of this project, in order to formulate a comprehensive description of core stability which will be used throughout this dissertation.

Definition

In early research,[79] core stability was defined as 'the ability of the lumbopelvic hip complex to prevent buckling of the vertebral column and return it to equilibrium following perturbation.' Panjabi[75] defined it as 'the capacity of the spinal stabilizing system to maintain the intervertebral neutral zones within physiological limits through functional integration of three subsystems (the passive spinal column, the active spinal muscles and the neural control unit).' Liemohn et al.[62] elaborated on this concept by defining core stability as 'the functional integration of these three subsystems in a manner that allows for an individual to maintain the intervertebral neutral zones within physiologic limits while performing activities of daily living.' These early studies focused on the concept of core (or spinal) stability and how it relates to low back pain.

Kibler et al.[56] identified the importance of this functional integration of the three subsystems during upper and lower extremity kinetic chain activities and athletic performance. The functioning of the kinetic chain during athletic tasks was described as the coordinated, sequenced activations of body segments that place the distal segment in the optimum position at the optimum velocity with the optimal timing to produce the desired task.[80] As such, Kibler et al.[56] defined core stability as 'the ability to control the position and motion of the trunk over the pelvis and leg to allow optimum production, transfer and control of force and motion to the terminal segment in integrated kinetic chain activities to provide proximal stability for distal mobility.'

Functional anatomy

The anatomical elements contributing to what is described as the core vary from study to study, depending on whether it is used in the context of rehabilitation or athletic performance.[92] In the context of low back pain rehabilitation, the core has been described as a box or a double-walled cylinder with the abdominals as the front, paraspinal and gluteal musculature as the back, the diaphragm as the roof and the pelvic floor and hip girdle musculature as the bottom.[19,27,47] Meanwhile, other researchers focusing on sports performance have defined the core as including all anatomical structures between the sternum and the knees with a focus on the abdominal region and low back, whereas others conclude that the core musculature should also include the muscles in the shoulder and pelvic regions as they are critical for the transfer of energy from the larger torso to the smaller extremities, which may be more involved in athletic movement rather than everyday tasks.[56,92,99] Whether or not the musculoskeletal structures of the hip are part of the core is often discussed. Although some authors imply that hip musculature is not an integral aspect of core stability,[14] most researchers agree upon the importance of hip muscle capacities in providing core stability. Hip muscles are stabilizers of the trunk over the planted leg and provide power for forward locomotion.[56] They play a significant role within the kinetic chain, particularly for all ambulatory activities, in stabilizing the trunk and pelvis and, in transferring force between the lower extremities and the pelvis and spine.[23,56,60,80,115] For example, van Wingerden et al.[103] showed that the biceps femoris and gluteus maximus can increase sacroiliac joint stabilization through their specific and massive attachments to the sacrotuberous ligament. Their study also indicated that the erector spinae and hip extensor muscles clearly interact to provide lumbopelvic stabilization. In conclusion, hip musculature is generally considered as a part of the core anatomy since these muscles connect the lower extremities to the pelvic girdle, allowing force to be transferred throughout the kinetic chain.[11]

The complex integration of the anatomical elements of the core and, the separate processes that work together to bring about core stability to provide proximal stability for distal mobility have also been described extensively. Besides postulating an early operational definition of core stability, Panjabi[75] also provided a fundamental insight into the anatomical structures to achieve core stability. He attributed the integration of the passive spinal column, active spinal muscles and neural control unit to achieve sufficient stability of the spine, without defining which specific anatomical structures. Cholewicki and VanVliet[21] reported that all trunk muscles, including abdominal as well as back musculature, contribute to core stability. These different muscles each provide a functional contribution towards core stability and they have been shown repeatedly to be the most important structures in maintaining core stability under various conditions.[19,32] No single muscle possesses a dominant responsibility in providing core stability.[21] However, a functional core musculature classification, based on their anatomical positioning and physiology, is often used to describe their contribution to stability.[12,24] Core muscles can be classified into a global system and a local system. The smaller deepest layer muscles that originate and insert segmentally are the main contributors to the local system and, the larger superficial or outer layer muscles of the trunk lacking segmental vertebral insertions are the major contributors to the global system. The local system plays a major stabilizing role in providing proprioceptive input for coordination and segmental movement control. On the other hand, the muscles of the global system can either have a stabilizing function where they generate force in order to control range of motion (ROM) during movement or, they can have a mobilizing function where they generate large torque to produce movement in daily living or athletic activities.[24] Research has identified the multifidus, transversus abdominis and the internal obliques as part of the local system, whereas the longissimus thoracis, rectus abdominis, external obliques and hip musculature are part of the global system. It is suggested that global musculature facilitates force production and transfer throughout the kinetic chain since these global muscle groups are interconnected with each other, as one muscle insertion is connected to the next muscle's origin via a common structure, such as the iliac crest (visualized in Figure 1).[12,74,105] The role of core musculature in providing core stability is best understood as the pre-programmed integration of local, single-joint muscles and multi-joint muscles to provide proximal stability for distal mobility.[56]

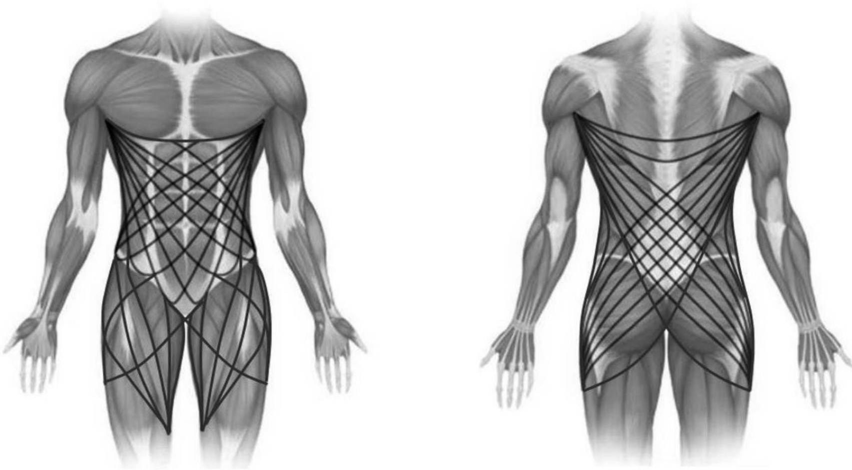


Figure 1 Ventral and dorsal view of global core musculature and the trunk-lower extremity interconnectivity (Adapted from Page et al.[74])

Core stability functioning

Optimal functioning of these anatomical structures to provide core stability relies on different musculoskeletal capacities.[8,19,26,30,33] It requires substantial core muscle strength, endurance, proprioception and neuromuscular control. **Core muscle strength** can be defined as the ability of the muscles to exert or withstand force to create stability through contractile forces and intra-abdominal pressure.[20,36] Greater core muscle activation leads to greater stability, however, too much strength or force could possibly be the cause of more instability if not directed correctly.[36] Besides core muscle strength, another component of core stability is represented by **core muscle endurance** or the ability to maintain the generated force.[60]

Although core strength contributes significantly towards core stability and is important for improvements in sports related performance measures,[66] it is suggested that core muscle endurance is more important to stability than muscle strength.[67] Stability of the core requires that the musculature be co-contracted for substantial durations but at relatively low levels of contraction.[65] It is this co-contraction of many muscles, required at relatively low activation levels, which optimizes stability of the spine and tissue load. This combination of low activation and recruitment of many muscles optimizes the compressive loading of the spine with stiffness to maximize spine resilience for extended time periods.[19,66]

The importance of **sensorimotor control** in providing core stability, besides core muscle strength and core muscle endurance, has also been described extensively. There is an increasing emphasis on sensorimotor control or the integrated actions of the muscle system in maintaining stability. Efficient movement and the maintenance of dynamic stability are more complex than merely adequate force production from the muscles.[14] The muscular activity 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 since it increases stability.[20] The sensorimotor control system is generally described as the sensory, motor, and central integration and processing components involved in maintaining joint homeostasis during bodily movements and this system relies on afferent **proprioceptive input** and the following efferent **neuromuscular dynamic response** for maintaining functional joint stability.[15,45,84]

Based on current literature and own expertise on core stability, its anatomy and functioning, the following description will be used throughout this dissertation to address core stability and, its components needed for optimal functioning are visualized in Figure 2:

> Core stability is the foundation of trunk, lumbopelvic and hip dynamic control that allows for optimal production and control of force and motion, which is transferred throughout the kinetic chain.[51,56] **Core stability** relies on different musculoskeletal capacities for efficient functioning and, achieving core stability requires optimal employment of **core muscle strength and endurance**, **proprioception and neuromuscular control**.[5,19,32,40,46,60] From an anatomical point of view, the musculoskeletal core of the body refers to the osseous and soft tissue structures of the lumbopelvic, abdominal and hip regions.[12,14,23,46,56] Core stability results in safe and controlled movement local and distal to the core, and is considered as an important contribution in maintaining dynamic joint stability throughout the kinetic chain during functional movement.[2,10,14]

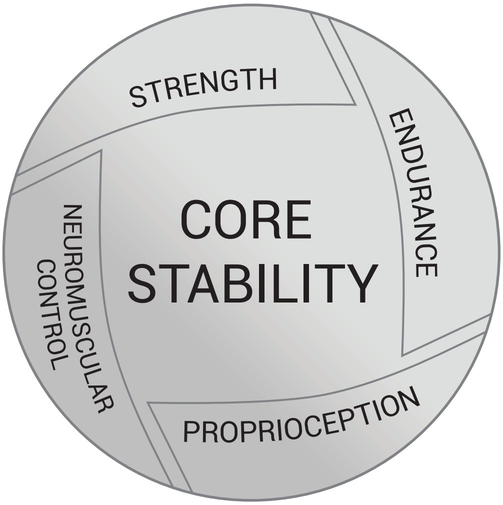


Figure 2 The core stability model with the components needed for optimal functioning

2.2 Assessment of core stability

Introduction

Since core stability is a complex interaction of musculoskeletal components that work synergistically, there is no single test that accurately measures the ability of an individual to exert this skill.[115] Consequently, each component should be evaluated in order to obtain a complete representation of core stability.[73] In general, a specific assessment method to evaluate core stability is often selected based on the component of core stability of interest or the goal of the study. However, these tests are often used interchangeably for the single purpose of measuring core muscle capacity.[115] In current literature, a multitude of tests to evaluate the different components of core stability are described. The different components are sometimes evaluated in lab situations with expensive equipment or with the use of not commercially available devices. As such, there is limited use for these devices in clinical practice when compared to clinical screening tests to measure core stability.[62,104,120] However, a frequently encountered issue in studies using such clinical screening measures is the insufficient reliability and/or validity of these tests.[35,42] In general, reliability refers to the reproducibility, consistency, or repeatability of a measure or test.[42,50] When reliability of human observations is determined, two forms of reliability are generally discussed: intra-tester reliability (the degree to which measurements taken by the same observer are consistent) and inter-tester reliability (the degree to which measurements taken by different observers are similar).[30] Better reliability implies better precision of single measurements.[50] Furthermore, adequate reliability contributes to responsiveness of a measure for better tracking of changes in measurements in research or practical settings. On the other hand, validity is generally defined as the degree to which a meaningful interpretation can be inferred from a measure or test or in other words, the degree to which a test measures what it is supposed to measure. Both reliability and validity are important since a clinical measure can be reliable without being valid; however, reliability is in general considered a prerequisite for validity.[42] Due to the vast amount of tests used to evaluate different components of core stability and the often contradicting evidence with regards to reliability and validity, a brief overview on core stability testing will be presented below.

Core muscle strength

Trunk flexion, extension and rotation strength have been hypothesized to contribute to core stability by generating and controlling forces along the kinetic chain to maximize stability and even athletic function.[56] Furthermore, an optimal trunk extension/flexion strength ratio has been described as essential for control of dynamic joint stability during functional movement.[82] Different aspects of muscle strength can be evaluated with a myriad of measurement methods. Stationary dynamometers (for isometric, isoinertial, or isokinetic strength testing), manual muscle testing (MMT) and handheld dynamometry (HHD) have been described as available methods to evaluate muscle strength.[6] For example, isokinetic tests measure muscle work performed at a constant velocity. This sort of testing is unique because it measures muscle torque at constantly changing joint angles, which presumably resembles a dynamic activity more closely.[115] However, the use of these dynamometers in clinical practice is limited since they are expensive, not easy to use and, training of the administrator is required. On the other hand, HHD provides a quantified measurement of strength and its ease of use, low cost and convenient size may justify a widespread clinical use.[91] Furthermore, it has been described extensively as a valid and reliable measurement method for evaluating upper and lower extremity muscle strength in a healthy population, provided the same participant position and the same standardized test method is used for every test.[91] **HHD** to assess maximal isometric hip muscle strength has already been established to be reliable and valid.[69,97] Although HHD has already been proven to be a reliable and valid test method and it has already been used to measure trunk muscle strength in previous research, there is currently no scientific evidence for HHD as a reliable and valid test to accurately measure maximal isometric trunk muscle strength.[70,82] Therefore, research into reliability and validity of HHD to measure maximal isometric trunk muscle strength is needed in order to gain insight into the strength capacities of these core muscle groups.

Core muscle endurance

The majority of measures to identify deficiencies in core muscle performance are clinical isometric trunk holding tests which are commonly used to measure the endurance capacity and fatigability of the core musculature.[13,25,60,67] These tests require minimal, inexpensive equipment and are safe and simple to perform in a clinical environment where endurance capacity is evaluated by recording the maximum time a subject can maintain a correct test position. Compared to core muscle strength tests, endurance tests have been suggested to be more reliable.[106]

These tests can be divided into tests that measure endurance capacities of the dorsal core musculature (trunk extension muscles), the ventral core musculature (trunk flexion and rotation muscles) or the lateral core musculature (trunk lateral flexion and rotation muscles). Endurance capacity of the trunk extensor muscles is often measured with the **Biering-Sørensen test**,[13] or an adapted version of this test.[25] This test is typically performed with the subject in a prone position with the pelvis on the edge of a treatment table and the legs strapped to this table. A horizontal position of the trunk is held as long as possible, with the arms crossed. Good to excellent reliability for this test has been calculated for healthy subjects as well as for patient populations.[35,55,59,93] Furthermore, validity for this test has been established based on EMG-analysis in a healthy population.[25] Variations in fixation methods have been described and dynamic versions of this test have also been used in research, however, the latter test variation is believed to measure submaximal dynamic muscle strength instead of muscle endurance.[70,83]

The **side-bridging test**, as described by McGill et al.,[67] is commonly used to measure lateral and ventral core muscle endurance. Reliability for this test has been shown to be excellent.[35,55] On the other hand, there is only limited evidence for validity of this test in current literature. Construct validity of this test was only suggested in one study in which subjects reported the reason for termination of the side-bridging test was fatigue of the lateral trunk musculature.[38] In another study, content validity of this test to measure physical capacity was approved by an expert panel.[58]

Abdominal core muscle endurance capacity is often measured using the flexor endurance test, as described by McGill et al.,[67] or with variations on this test.[52] Good to excellent reliability values for these tests have been established.[35,52,93] However, validity of these tests has not yet been examined. The **prone bridging test**, an isometric holding test in prone position, is also commonly used to measure the endurance capacity of the abdominal core muscles and has been theorized to be a more functional test for abdominal core muscle endurance compared to the flexor endurance test.[4,106,108] Reliability and especially validity of the prone bridging endurance test in a healthy population have not yet been researched thoroughly. Studies researching the reliability of the prone bridging test report conflicting results. Low, moderate as well as excellent reliability values have all been reported.[26,88,108] On the other hand, research into the validity of the prone bridging test is sparse and often applied to modified versions of this test.[98] Therefore, research into reliability and validity of prone bridging test to measure abdominal muscle endurance capacity in a healthy population is needed in order for this test to be used for screening purposes.

Core sensorimotor control

The sensorimotor system relies on the afferent proprioceptive input and the following efferent neuromuscular output.[15,45,84] The need to assess proprioceptive ability and neuromuscular control accurately is widely accepted, however, there is great disagreement to the most appropriate and accurate method and the best measurement technique has yet to be determined.[45] Ideally, proprioception is measured in three planes for passive motion threshold, directional motion perception and repositioning accuracy.[76] However, only evaluating a subjects spinal repositioning capacities is commonly used to measure core proprioception.[45] Repositioning capacities of the trunk are often measured with the use of self-fabricated lab equipment on which a subject can sit or lay down.[76,95,121] The subject is passively rotated on these machines or is able to actively rotate the trunk with the aim of replicating a predefined lumbopelvic position. Even though validity for some of these methods has been established, their use in clinical practice is very limited since they are not readily available to clinicians for the identification of proprioceptive deficits. In one clinical study, subjects were placed in a sitting positing with a neutral spine and were asked to reposition themselves into this position after having actively moved the trunk.[93] However, to quantify the repositioning capacities, 3D lab generated data were used, again limiting its use for clinical practice. There seems to be need for a method to evaluate core proprioception without the use of equipment, which is based on **lumbopelvic position-reposition** capacity and can be used in clinical practice.

Different methods to identify deficits in core neuromuscular control have been described. Ideally, deficits in neuromuscular control of the core should be diagnosed based on controllability, or lack hereof, of global movement during athletic maneuvers.[119] This can be accomplished by performing athletic movement, such as a drop jump or sprinting movements, while 3D movement analysis is performed.[90,104] Neuromuscular control is also often quantified by measuring muscle activation patterns (coordination) during movement by using electromyography (EMG).[14] Radebold et al.,[81] for example, used a sitting apparatus with a quick force release after isometric trunk exertions against trunk flexion, extension and lateral flexion while measuring EMG activity of the trunk muscles as a measure of neuromuscular control. This method of measuring core muscle activation patterns can also be applied during functional movements, such as sprinting.[89] It is clear that the aforementioned methods of measuring core neuromuscular control have limited use in clinical practice. More recently however, a clinical test to evaluate core neuromuscular control was specifically developed for use in clinical practice. Elgueto-Cancina et al.[33] assessed core neuromuscular control by evaluating a repeated lumbopelvic movement on five categories: quality of the lumbopelvic motion, control of the adjacent areas, preference of motion direction, breathing, and the amount of good quality repetitions. The five criteria were evaluated afterwards using a rating scale. Test scoring for this **lumbopelvic control test** has been shown to be reliable,[24] and validity of this test in a healthy population is supported.[34]

Dynamic core stability testing

Since core stability is important for providing dynamic joint stability during functional movement, it has been suggested that besides evaluation of the separate components of core stability, assessment of core stability should also be dynamic, and should include tests which evaluate specific functions and directions of three planar movement in an upright position.[56,110] To assess dynamic core control, Kibler et al.[56] suggested six positions and movements for a subject to perform in order for the investigator to look for movement pattern deviations. However, these tests are based on empirical evidence and, only low to moderate reliability was shown for these tests based on test evaluation with a 4-point scale for movement quality.[108]

Assessment of postural stability has been suggested as an indicator for the product of adequate core stability since dynamic balance is reliant on the different components of core stability (strength, neuromuscular control and proprioception) to develop internal muscle moments to counteract the external moments generated by body mass displacement.[23,55,62] Postural stability is often measured with the use of reliable and validated equipment such as the Neurocom Balance Master.[55,93] Liemohn et al.[62] developed a measurement device to measure core stability through balance tests in which actual core stability training postures were replicated. For this purpose, a stability platform was used on which balance had to be maintained in three different functional positions. As with many tests which employ mechanical equipment, the use of these methods is limited in clinical practice. Other tests to measure dynamic postural stability without the use of equipment, such as the **Star Excursion Balance Test (SEBT)**, have been shown to be reliable and valid in a healthy population.[39,78] Another widely used dynamic test which requires optimal integration of different core stability components is **the lateral step down test** and has already been suggested as a functional core stability test for patients with nonspecific low back pain.[55] This test incorporates different components needed for core stability such as core muscle strength, neuromuscular control and proprioception. Therefore, this test can also be viewed as an indicator for the cooperation between different core stability components.[68,72] Validity has not yet been established, excellent reliability has only been demonstrated in patient populations and,[55,77] only low to moderate reliability was shown in a healthy population.[18] The protocol for this test needs to be adapted with regards to test standardization and test scoring in order for it to be used in clinical practice for identifying deficiencies in movement control and movement pattern deviations.

There is not one single appropriate test to evaluate core stability given its complex nature. Various methods and tests exist to evaluate different components of core stability.

A recent study suggested that in order to gain insight into core stability as a whole and for it to be used in the fields of injury prevention, rehabilitation and athletic training, assessment of core stability should be based on a comprehensive test battery where the different components of core stability are evaluated. In order to be clinically relevant, these tests should be valid, reliable, feasible and easy to perform.[28] To assess core stability with the goal of investigating its role in the development of lower extremity injuries, established valid and/or reliable clinical tests from current literature will be complemented with novel tests for which validity and/or reliability will be evaluated.

Further research is needed to investigate validity and/or reliability in a healthy population of the **prone bridging test** to evaluate abdominal core muscle endurance, **HHD** to measure trunk flexor/extensor strength, the **lumbopelvic position-reposition test** to evaluate core proprioception and the **lateral step down test** as a dynamic core stability test.

2.3 The core stability - lower extremity link

Core stability and lower extremity functioning

Core stability has been implied numerous times to influence lower limb functioning.[29,43,65] Besides its local functions of stability and force generation, core activity is believed to be involved in almost all extremity movement.[14] Early research to propose the relationship between core stability and lower extremity functioning was executed by Bouisset.[16] The author suggested that stabilization of the pelvis and trunk must occur before the initiation of voluntary extremity movements. In addition, the support must vary according to the parameters of the planned movement, posture, and the uncertainty about the upcoming tasks. These principles were further explored by Hodges & Richardson.[49] Based on EMG analysis, these authors found that abdominal and multifidus muscles contract in anticipation of reactive forces produced by lower limb movement. It was hypothesized that co-contraction of these muscles helped in creating a rigid cylinder by increasing abdominal pressure and, that it occurred in order to stiffen the lumbar spine before initiation of large movements of the limbs.[14,56] On the contrary, further research established that three-dimensional preparatory trunk motion preceded unilateral limb movements.[48] These preparatory movements were opposite in direction to those caused by the reactive moments resulting from movement of the limb. These results confirmed that anticipatory postural adjustments involve movements and not rigidification of the trunk.[48] This relationship has also been demonstrated in more functional situations. For example, Saunders et al.[87] found an association between altered lumbopelvic motion and trunk muscle activity during locomotion at different speeds and modes of locomotion. In conclusion, in the temporal sequence of many dynamic tasks, core muscle activity precedes lower extremity muscle activity and provides a stable foundation, which allows for safe and controlled movement distal to the core, and is considered as an important contributor in maintaining dynamic joint stability in the kinetic chain during locomotion.[2,9] The core is connected to the lower extremity anatomically as well. The thoracolumbar fascia covers the deep muscles of the back and the trunk, has three discernible layers and connects the lumbar vertebrae with the lower extremity through the latissimus dorsi, psoas major, and gluteal muscles (as visualized in Figure 1 above)[32] and creates a stabilizing effect by forming a corset around the abdomen together with the multifidus muscles posteriorly, the abdominal fascia anteriorly and the oblique muscles laterally.[3] Furthermore, the hip musculature acts in conjunction with the quadratus lumborum muscle to stabilize the trunk over the lower limb and transfers force from the lower extremities to the pelvis and spine.[3] The apparent link between core stability and lower extremity functioning has been confirmed since the association between core stability measures and lower extremity kinematics has been established and,[116] core training has been proven to influence lower extremity biomechanics and,[31,86] it was found to modify and enhance sports performance.[17,53,110]

Core stability and lower extremity injury

Numerous musculoskeletal injuries occur each year caused by sports, resulting in decreased physical activity and work time lost in addition to medical costs.[71] The most common injury sites of these musculoskeletal injuries in collegiate athletes are located on the lower extremity, including hip, knee, lower leg, and ankle injuries.[71] One study reported a total number of 4350 musculoskeletal injuries in collegiate athletes during one academic year, of which 2298 (52.8%) LEI (injury rate of 1.33 per 1000 athletic exposures).[37] A crucial step towards injury prevention is establishing the etiology and mechanisms of the injury, by means of risk factor assessment.[101] Many injury risk factors, both extrinsic and intrinsic, for the development of LEI have already been suggested.[114] Extrinsic risk factors refer to environmental variables and are considered to determine the load which makes the individual susceptible to injury, whereas intrinsic risk factors are related to the individual biological and psychological characteristics and determine the load tolerance.[100] Furthermore, all risk factors can be divided into modifiable and non-modifiable factors.[8] With regards to research into risk factor identification and injury prevention, it has been suggested that non-modifiable risk factors such as gender and age may be of interest, it is however important to study factors which are potentially modifiable through physical training or behavioral approaches, such as strength, balance, or flexibility.[8] Research into modifiable intrinsic risk factors for LEI often focusses on locally situated risk factors (risk factors situated at the site of the injury). For example, inadequate neuromuscular control of musculature surrounding the knee has been associated with the development of anterior cruciate ligament injury and,[44] decreased ankle muscle strength and altered foot biomechanics, including excessive and prolonged foot pronation, are associated with inversion ankle sprains.[111,113]

However, there is an increase in research investigating non-locally situated risk factors as they might also play an important role in the development of LEI and, these non-local risk factors can be located proximally or distally from the injury site.[22] Inadequate core stability is suggested to influence lower extremity kinematics and is proposed as a contributor in the proximal-to-distal directed mechanism in the development of LEI.[28] Strength of core musculature for example is proven to be essential to control hip abduction, subsequent internal rotation of the femur, and potentially more distal movement,[51,60] which could increase susceptibility for injury since distal movement, such as prolonged foot pronation, has been implicated in numerous functional changes to the lower limb.[22] In addition, suboptimal endurance of the core musculature results in inhibition of specific lower extremity muscles, resulting in kinetic and kinematic changes during dynamic tasks.[40,41,94] Therefore, it is hypothesized that impaired core stability increases vulnerability in the development of LEI through uncontrolled joint displacements or accessory movements throughout the kinetic chain.[22,56] This hypothesis is supported with evidence that core muscle endurance is effectively linked with running kinematics.[57]

A significant share of LEI are lower extremity overuse injuries (LEOI) and are traditionally defined as injuries that occur with gradual onset over time and are thought to be the predominant injury type as a result of repetition of similar movement patterns such as running, jumping, landing and cutting.[7,61] It is believed that a large proportion of lower extremity sports injuries are LEOI, since popular sport (e.g. recreational sports, gymnastics, basketball, football and volleyball) and recreational physical activities are often associated with running and/or jumping.[54] For example, one study with a multisport cohort reported a total of 1317 injuries in 573 collegiate male and female athletes of which 386 (29.3%) overuse injuries.[118] LEOI have even been reported as being as high as 68% of all registered LEI in runners.[96] The etiology of overuse injuries remains largely unknown,[102] and local intrinsic factors have already been suggested.[63,112,117] Bearing in mind the link with lower extremity functioning, core stability, as a non-local risk factor, could have a crucial role in developing LEOI.

There is currently a lack of studies investigating core stability and its role in the development of LEI.[22,28] As such, the lack of transparency in the concept of core stability as a risk factor and, the absence of valid and/or reliable assessment methods to describe different aspects of core stability in a homogenous population might have led to suboptimal implementation of core stability as a preventative screening tool in clinical practice. As it is still unclear to this day how impaired core stability could lead to injuries, researching and identifying the relationship between impaired core stability and LEI could have important implications in the fields of injury prevention and rehabilitation.

Furthermore, the lack of evidence for core stability as a risk factor for the development of LEOI has already been highlighted and further research to establish the association between the different components of core stability and overuse injuries is warranted as such.[28]

3 Background and aims

Core stability has been implied to influence lower extremity functioning. Therefore, inadequate core stability, as a non-local, modifiable, intrinsic risk factor, could play a role in the development of lower extremity injuries (LEI). Inadequate core stability is believed to increase uncontrolled joint displacements or accessory movements throughout the kinetic chain and could therefore increase susceptibility for the development of injuries.[22,104,109]

Based on current literature, there seems to be limited proof for the role of core stability in the development of LEI.[28] Furthermore, there is no single measure for determining core stability since it relies on different musculoskeletal capacities.[28] As such, the lack of transparency of the concept of core stability as a risk factor and, the absence of valid and/or reliable assessment methods to describe different aspects of core stability in a single population have led to suboptimal implementation of the assessment of core stability as a screening tool in clinical practice.

Specific aims of this dissertation are:

1. Providing an overview of current evidence for core stability as a risk factor for lower extremity injuries.
2. Investigating reliability and/or validity of existing or novel clinical tests to evaluate components of core stability in a healthy population. In order to complement

other valid and reliable tests, certain tests will be investigated with regards to standardization, test protocol and scoring methods.

3. To prospectively investigate the different components of core stability as a risk factor for the development of lower extremity overuse injuries (LEOI).

AIM I: Providing an overview of current evidence for core stability as a risk factor for lower extremity injuries

A first step towards gaining insight into the association between core stability and the development of LEI is to gather the current knowledge from present literature. Therefore, the main purpose of **chapter I** is to summarize the available literature on the role of core stability as an intrinsic risk factor in the development of LEI in a healthy athletic population. In order to achieve this goal, a systematic review of the literature will be performed. This review will present the reader with an overview of current knowledge and will discuss these findings and explore the association between various components attributed to core stability and LEI.

AIM II: Investigating reliability and/or validity of clinical tests to evaluate components of core stability in a healthy population

Accurate measurement of core stability could prove beneficial in the fields of musculoskeletal injury prevention and athletic training. No single test is available to evaluate core stability in an individual since it is a complex interaction of musculoskeletal capacities that work synergistically. In current literature, there is a multitude of tests to evaluate the different components of core stability. Laboratory tests often have limited use in clinical practice because of high costs or low availability of the testing equipment. Easy to use clinical tests on the other hand often have low reliability and/or validity. In addition to clinical core stability tests for which reliability and/or validity has already been established, in **chapter II**, reliability and/or validity of clinical tests to measure core muscle strength, core muscle endurance and sensorimotor control of the core will be investigated and will be discussed in three parts. In **part I**, reliability and validity of the prone bridging test to measure abdominal core muscle endurance capacities will be examined. In **part II**, reliability and validity of two clinical tests to measure trunk flexor and trunk extensor strength will be examined and in **part III**, reliability of two functional clinical tests to evaluate trunk and lumbopelvic neuromuscular control and proprioception will be explored. Reliability and/or validity of these tests will be investigated in order for them to be used complementary with other reliable and/or valid tests to measure the different components of core stability.

AIM III: To prospectively investigate the different components of core stability as a risk factor for the development of lower extremity overuse injuries

Proximally located intrinsic risk factors have already been suggested and investigated in the development of distally located LEI. Impaired core stability has been associated with acute LEI.[28,82] However, there is a lack of research investigating core stability and its role in the development of LEOI. Therefore, in **chapter III**, a prospective study was set up to investigate the association between different components of core stability and LEOI. Risk factors are typically examined in prospective cohort studies in which the characteristics of an injured individual can be compared with non-injured individuals and, all data are collected prospectively in time which means that potential risk factors are measured before the actual injury occurs during the follow-up period. The aim of this prospective study was to investigate the different components, necessary for adequate core stability, as possible risk factors in the development of LEOI in an active population. These components include core muscle strength, core muscle endurance, core neuromuscular control and proprioception and, dynamic core stability performance.

References

1. Abdelraouf OR, Abdel-Aziem AA. The relationship between core endurance and back dysfunction in collegiate male athletes with and without nonspecific low Back pain. *Int J Sports Phys Ther.* 2016;11(3):337-344.
2. Akuthota V, Ferreiro A, Moore T, Fredericson M. Core stability exercise principles. *Curr Sports Med Rep.* 2008;7(1):39-44.
3. Akuthota V, Nadler SF. Core strengthening. *Arch Phys Med Rehabil.* 2004;85(3):86-92.
4. Ambegaonkar JP, Cortes N, Caswell S V, Ambegaonkar GP, Wyon M. Lower extremity hypermobility, but not core muscle endurance influences balance in female collegiate dancers. *Int J Sports Phys Ther.* 2016;11(2):220-229.
5. Anderson K, Behm DG. The impact of instability resistance training on balance and stability. *Sport Med.* 2005;35(1):43-53.
6. Arnold CM, Warkentin KD, Chilibeck PD, Magnus CRA. The reliability and validity of handheld dynamometry for the measurement of lower-extremity muscle strength in older adults. *J Strength Cond Res.* 2010;24(3):815-824.
7. Bahr R. No injuries, but plenty of pain? On the methodology for recording overuse symptoms in sports. *Br J Sports Med.* 2009;43(13):966-972.
8. Bahr R, Holme I. Risk factors for sports injuries-a methodological approach. *Br J Sports Med.* 2003; 37(5):384-392.
9. Barr KP, Griggs M, Cadby T. Lumbar stabilization part 1. *Am J Phys Med Rehabil.* 2007;86(1):72-80.
10. Barr KP, Griggs M, Cadby T. Lumbar stabilization part 2. *Am J Phys Med Rehabil.* 2005;84(6):473-480.
11. Behm DG, Drinkwater EJ, Willardson JM, Cowley PM. Canadian society for exercise physiology position stand: The use of instability to train the core in athletic and nonathletic conditioning. *Appl Physiol Nutr Metab.* 2010;35(1):109-112.
12. Bergmark A. Stability of the lumbar spine: A study in mechanical engineering. *Acta Orthop.* 1989;230:1-54.
13. Biering-Sørensen F. Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine (Phila Pa 1976).* 1984;9(2):106-119.
14. Borghuis J, 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.
15. Boucher JA, Abboud J, Descarreaux M. The influence of acute back muscle fatigue and fatigue recovery on trunk sensorimotor control. *J Manipulative Physiol Ther.* 2012;35(9):662-668.
16. Bouisset S. Relationship between postural support and intentional movement: biomechanical approach. *Arch Int Physiol Biochim Biophys.* 1991;99(5):A77-92.
17. Butcher SJ, Craven BR, Chilibeck PD, Spink KS, Grona SL, Sprigings EJ. The effect of trunk stability training on vertical takeoff velocity. *J Orthop Sport Phys Ther.* 2007;37(5):223-231.
18. Chmielewski TL, Hodges MJ, Horodyski M, Bishop MD, Conrad BP, Tillman SM. park. *J Orthop Sports Phys Ther.* 2007;37(3):122-129.
19. Cholewicki J, McGill SM. Mechanical stability of the in vivo lumbar spine: Implications for injury and chronic low back pain. *Clin Biomech.* 1996;11(1):1-15.
20. Cholewicki J, Simons APD, Radebold A. Effects of external trunk loads on lumbar spine stability. *J Biomech.* 2000;33(11):1377-1385.
21. Cholewicki J, VanVliet Iv JJ. Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions. *Clin Biomech.* 2002;17(2):99-105.
22. Chuter VH, Janse de Jonge XA. Proximal and distal contributions to lower extremity injury: a review of the literature. *Gait Posture.* 2012;36(1):7-15.
23. Colston MA. Core stability, part 1: Overview of the concept. *Int J Athl Ther Train.* 2012;17(1):8-13.
24. Comerford MJ, Mottram SL. Review article: Movement and stability dysfunction - Contemporary developments. *Man Ther.* 2001;6(1):15-26.
25. Coorevits P, Danneels L, Cambier D, Ramon H, Vanderstraeten G. Assessment of the validity of the Biering-Sørensen test for measuring back muscle fatigue based on EMG median frequency characteristics of back and hip muscles. *J Electromyogr Kinesiol.* 2008;18(6):997-1005.
26. Cowley PM, Swensen TC. Development and reliability of two core stability field tests. *J Strength Cond Res.* 2008;22(2):619-624.

27. Daggfeldt K, Thorstensson A. The role of intra-abdominal pressure in spinal unloading. *J Biomech.* 1997;30(11-12):1149-1155.
28. De Blaiser C, Roosen P, Willems T, Danneels L, Vanden Bossche L, De Ridder R. Is core stability a risk factor for lower extremity injuries in an athletic population? A systematic review. *Phys Ther Sport.* 2018;30:48-56.
29. Dierks T a, Manal KT, Hamill J, Davis IS. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J Orthop Sports Phys Ther.* 2008;38(8):448-456.
30. Downing SM. Reliability : on the reproducibility of assessment data. *Med Educ.* 2004;38(9):1006-1012.
31. Earl JE, Hoch AZ. A proximal strengthening program improves pain, function, and biomechanics in women with patellofemoral pain syndrome. *Am J Sport Med.* 2011;39(1):154-163.
32. Ebenbichler GR, Oddsson LIE, Kollmitzer J, Erim Z. Sensory-motor control of the lower back: Implications for rehabilitation. *Med Sci Sports Exerc.* 2001;33(11):1889-1898.
33. Elgueta-Cancino E, Schabrun S, Danneels L, Hodges P. A clinical test of lumbopelvic control: Development and reliability of a clinical test of dissociation of lumbopelvic and thoracolumbar motion. *Man Ther.* 2014;19(5):418-424.
34. Elgueta-Cancino E, Schabrun S, Danneels L, van den Hoorn W, Hodges P. Validation of a clinical test of thoracolumbar dissociation in chronic low back pain. *J Orthop Sport Phys Ther.* 2015;45(9):703-712.
35. Evans K, Refshauge KM, Adams R. Trunk muscle endurance tests: Reliability, and gender differences in athletes. *J Sci Med Sport.* 2007;10(6):447-455.
36. Faries MD, Greenwood M. Core training: Stabilizing the confusion. *Strength Cond J.* 2007;29(2):10-25.
37. Fernandez WG, Yard EE, Comstock RD. Epidemiology of lower extremity injuries among U.S. high school athletes. *Acad Emerg Med.* 2007;14(7):641-645.
38. Greene PF, Durall CJ, Kernozek TW. Intersession reliability and concurrent validity of isometric endurance tests for the lateral trunk muscles. *J Sport Rehabil.* 2012;21(2):161-166.
39. Gribble PA, Hertel J, Plisky P. Using the star excursion balance test to assess dynamic postural-control deficits and outcomes in lower extremity injury: A literature and systematic review. *J Athl Train.* 2012; 47(3):339-357.
40. Hammill RR, Beazell JR, Hart JM. Neuromuscular consequences of low back pain and core dysfunction. *Clin Sports Med.* 2008;27(3):449-462.
41. Hart JM, Fritz JM, Kerrigan DC, Saliba EN, Gansneder BM, Ingersoll CD. Reduced quadriceps activation after lumbar paraspinal fatiguing exercise. *J Athl Train.* 2006;41(1):79-86.
42. Hayen A, Dennis RJ, Finch CF. Determining the intra- and inter-observer reliability of screening tools used in sports injury research. *J Sci Med Sport.* 2007;10(4):201-210.
43. Hewett TE, Ford KR, Myer GD. Anterior cruciate ligament injuries in female athletes: Part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. *Am J Sports Med.* 2006;34(3): 490-498.
44. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* 2005;33(4):492-501.
45. Hewett TE, Paterno M V, Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop Relat Res.* 2002;(402):76-94.
46. Hibbs AE, Thompson KG, French D, Wrigley A, Spears I. Optimizing performance by improving core stability and core strength. *Sport Med.* 2008;38(12):995-1008.
47. Hodges PW. Core stability exercise in chronic low back pain. *Orthop Clin North Am.* 2003;34(2):245-254.
48. Hodges PW, Cresswell AG, Daggfeldt K, Thorstensson A. Three dimensional preparatory trunk motion precedes asymmetrical upper limb movement. *Gait Posture.* 2000;11(2):92-101.
49. Hodges PW, Richardson CA. Contraction of the abdominal muscles associated with movement of the lower limb. *Phys Ther.* 1997;77(2):132-142.
50. Hopkins WG. Measures of reliability in sports medicine and science. *Sport Med.* 2000;30(4):1-15.
51. Ireland ML, Willson JD, Ballantyne BT, Davis IM. Hip strength in females with and without patellofemoral pain. *J Orthop Sport Phys Ther.* 2003;33(11):671-676.
52. Ito T, Shirado O, Suzuki H, Takahashi M, Kaneda K, Strax TE. Lumbar trunk muscle endurance testing: An inexpensive alternative to a machine for evaluation. *Arch Phys Med Rehabil.* 1996;77(1):75-79.

53. Jamison ST, McNally MP, Schmitt LC, Chaudhari AMW. The effects of core muscle activation on dynamic trunk position and knee abduction moments: Implications for ACL injury. *J Biomech*. 2013;46(13):2236-2241.
54. Järvinen M. Lower leg overuse injuries in athletes. *Knee Surg Sports Traumatol Arthrosc*. 1993;1(2):126-130.
55. Kahraman BO, Sengul YS, Kahraman T, Kalemci O. Developing a reliable core stability assessment battery for patients with nonspecific low back pain. *Spine (Phila Pa 1976)*. 2016;41(14):E844-E850.
56. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med*. 2006;36(3):189-198.
57. Koblbauer IF, van Schooten KS, Verhagen E a, van Dieën JH. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *J Sci Med Sport*. June 2013.
58. Larsson H, Tegern M, Monnier A, et al. Content validity index and intra- and inter- rater reliability of a new muscle strength/ endurance test battery for Swedish soldiers. *PLoS One*. 2015;10(7):1-13.
59. Latimer J, Maher CG, Latimer J, Maher CG. The reliability and validity of the Biering-Sorensen test in asymptomatic subjects and subjects reporting current or previous nonspecific low back pain. *Spine (Phila Pa 1976)*. 1999;24(20):2085-2090.
60. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc*. 2004;36(6):926-934.
61. Lian ØB, Engebretsen L, Bahr R. Prevalence of jumper s knee among elite athletes from different sports: A cross-sectional study. *Am J Sports Med*. 2005;33(4):561-567.
62. Liemohn WP, Baumgartner TA, Gagnon LH. Measuring core stability. *J Strength Cond Res*. 2005;19(3):583-586.
63. Mahieu NN, Witvrouw E, Stevens V, Van Tiggelen D, Roget P. Intrinsic risk factors for the development of achilles tendon overuse injury: a prospective study. *Am J Sport Med*. 2006;34(2):226-235.
64. Majewski-Schrage T, Evans TA, Ragan B. Development of a core-stability model: A Delphi approach. *J Sport Rehabil*. 2013;23(2):95-106.
65. McGill SM. Core training: Evidence translating to better performance and injury prevention. *Strength Cond J*. 2010;32(3):33-46.
66. McGill SM. Low back stability: From formal description to issues for performance and rehabilitation. *Exerc Sport Sci Rev*. 2001;29(1):26-31.
67. McGill SM, Childs A, Liebenson C. Endurance times for low back stabilization exercises: Clinical targets for testing and training from a normal database. *Arch Phys Med Rehabil*. 1999;80(8):941-944.
68. McMullen KL, Cosby NL, Hertel J, Ingersoll CD, Hart JM. Lower extremity neuromuscular control immediately after fatiguing hip-abduction exercise. *J Athl Train*. 2011;46(6):607-614.
69. Mentiplay BF, Perraton LG, Bower KJ, et al. Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: A reliability and validity study. *PLoS One*. 2015;10(10):1-18.
70. Moreland J, Finch E, Stratford P, Balsor B, Gill C. Interrater Reliability of Six Tests of Trunk Muscle Function and Endurance. *J Orthop Sport Phys Ther*. 1997;26(4):200-208.
71. Murphy DF, Connolly D a J, Beynnon BD. Risk factors for lower extremity injury: a review of the literature. *Br J Sports Med*. 2003;37(1):13-29.
72. Norcross MF, Halverson SD, Hawkey TJ, Blackburn JT, Padua DA. Evaluation of the lateral step-down test as a clinical assessment of hip musculature strength. *Athl Train Sport Heal Care*. 2009;1(6):272-278.
73. O'Connor S, McCaffrey N, Whyte E, Moran K. The development and reliability of a simple field based screening tool to assess core stability in athletes. *Phys Ther Sport*. 2016;20:40-44.
74. Page P, Frank CC, Lardner R. *Assessment and Treatment of Muscle Imbalance: The Janda Approach*. Champaign, Il: Human Kinetics; 2010.
75. Panjabi MM. The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. *J Spinal Disord*. 1992;5(4):383-9; discussion 397.
76. Parkhurst TM, Burnett CN. Injury and proprioception in the lower back. *J Orthop Sport Phys Ther*. 1994;19(5):282-295.
77. Piva SR, Fitzgerald K, Irrgang JJ, et al. Reliability of measures of impairments associated with patellofemoral pain syndrome. *BMC Musculoskelet Disord*. 2006;7:1-13.
78. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star excursion balance test as a predictor of lower extremity injury in high school asketball players. *J Orthop Sport Phys Ther*. 2006;36(12):911-919.

79. Pope MH, Panjabi M. Biomechanical definitions of spinal instability. *Spine (Phila Pa 1976)*. 1985;10(3):255-256.
80. Putnam CA. Sequential motions of body segments in striking and throwing skills: Descriptions and explanations. *J Biomech*. 1993;26:125-135.
81. Radebold A, Cholewicki J, Polzhofer GK, Greene HS. Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. *Spine (Phila Pa 1976)*. 2001;26(7):724-730.
82. Raschner C, Platzer HP, Patterson C, Werner I, Huber R, Hildebrandt C. The relationship between ACL injuries and physical fitness in young competitive ski racers: A 10-year longitudinal study. *Br J Sports Med*. 2012;46(15):1065-1071.
83. Reiman MP, Krier AD, Nelson JA, Rogers MA, Stuke ZO, Smith BS. Reliability of alternative trunk endurance testing procedures using clinician stabilization vs. traditional methods. *J Strength Cond Res*. 2010;24(3):730-736.
84. Riemann BL, Lephart SM. The sensorimotor system, part I: The physiologic basis of functional joint stability. *J Athl Train*. 2002;37(1):71-79.
85. Saeterbakken AH, van den Tillaar R, Seiler S. Effect of core stability training on throwing velocity in female handball players. *J Strength Cond Res*. 2011;25(3):712-718.
86. Sato K, Mokha M. Does core strength training influence running kinetics, lower-extremity stability, and 5000-M performance in runners. *J strenght Cond Res*. 2009;23(1):133-140.
87. Saunders SW, Schache A, Rath D, Hodges PW. Changes in three dimensional lumbo-pelvic kinematics and trunk muscle activity with speed and mode of locomotion. *Clin Biomech*. 2005;20(8):784-793.
88. Schellenberg KL, Lang JM, Chan KM, Burnham RS. A clinical tool for office assessment of lumbar spine stabilization endurance: Prone and supine bridge maneuvers. *Am J Phys Med Rehabil*. 2007;86(5): 380-386.
89. Schuermans J, Danneels L, Van Tiggelen D, Palmans T, Witvrouw E. Proximal neuromuscular control protects against hamstring injuries in male soccer players: A prospective study with electromyography time-series analysis during maximal sprinting. *Am J Sports Med*. 2017;45(6):1315-1325.
90. Schuermans J, Van Tiggelen D, Palmans T, Danneels L, Witvrouw E. Deviating running kinematics and hamstring injury susceptibility in male soccer players: Cause or consequence? *Gait Posture*. 2017;57:270-277.
91. Stark T, Walker B, Phillips JK, Fejer R, Beck R. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: A systematic review. *PM R*. 2011;3(5):472-479.
92. Stephenson J, Swank AM. Core training: designing a program for anyone. *Strength Cond J*. 2004;26(6):34.
93. Stevens VK, Bouche KG, Mahieu NN, Cambier DC, Vanderstraeten GG, Danneels LA. Reliability of a functional clinical test battery evaluating postural control, proprioception and trunk muscle activity. *Am J Phys Med Rehabil*. 2006;85(9):727-736.
94. Suter E, Lindsay D. Back muscle fatigability is associated with knee extensor inhibition in subjects with low back pain. *Spine (Phila Pa 1976)*. 2001;26(16):E361-6.
95. Taimela S, Kankaanpää M, Luoto S. The effect of lumbar fatigue on the ability to sense a change in lumbar position: A controlled study. *Spine (Phila Pa 1976)*. 1999;24(13):1322-1327.
96. Tenforde AS, Sayres LC, McCurdy ML, Collado H, Sainani KL, Fredericson M. Overuse injuries in high school runners: lifetime prevalence and prevention strategies. *PM R*. 2011;3(2):125-131.
97. Thorborg K, Petersen J, Magnusson SP, Hölmich P. Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scand J Med Sci Sport*. 2010;20(3):493-501.
98. Tong TK, Wu S, Nie J. Sport-specific endurance plank test for evaluation of global core muscle function. *Phys Ther Sport*. 2014;15(1):58-63.
99. Tse MA, McManus AM, Masters RSW. Development and validation of a core endurance intervention program: Implications for performance in college-age rowers. *J Strength Cond Res*. 2005;19(3):547-552.
100. van Mechelen W, Hlobil H, Kemper HC. Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Med*. 1992;14(2):82-99.
101. Van Tiggelen D, Wickes S, Stevens V, Roosen P, Witvrouw E. Effective prevention of sports injuries: A model integrating efficacy, efficiency, compliance and risk-taking behaviour. *Br J Sports Med*. 2008;42(8):648-652.

102. Van Wilgen CP, Verhagen EALM. A qualitative study on overuse injuries: The beliefs of athletes and coaches. *J Sci Med Sport*. 2012;15(2):116-121.
103. Van Wingerden JP, Vleeming A, Buyruk HM, Raissadat K. Stabilization of the sacroiliac joint in vivo: verification of muscular contribution to force closure of the pelvis. *Eur Spine J*. 2004;13(3):199-205.
104. Verrelst R, De Clercq D, Vanrenterghem J, Willems T, Palmans T, Witvrouw E. The role of proximal dynamic joint stability in the development of exertional medial tibial pain: a prospective study. *Br J Sport Med*. 2013.
105. Vleeming A, Pool-Goudzwaard AL, Stoeckart R, van Wingerden JP, Snijders CJ. The posterior layer of the thoracolumbar fascia. Its function in load transfer from spine to legs. *Spine (Phila Pa 1976)*. 1995;20(7):753-758.
106. Waldhelm A, Li L. Endurance tests are the most reliable core stability related measurements. *J Sport Heal Sci*. 2012;1(2):121-128.
107. Wang XQ, Zheng JJ, Yu ZW, et al. A meta-analysis of core stability exercise versus general exercise for chronic low back pain. *PLoS One*. 2012;7(12):1-7.
108. Weir A, Darby J, Inklaar H, Koes B, Bakker E, Tol JL. Core stability: inter- and intraobserver reliability of 6 clinical tests. *Clin J Sport Med*. 2010;20(1):34-38.
109. Wilkerson GB, Giles JL, Seibel DK. Prediction of core and lower extremity strains and sprains in collegiate football players: A preliminary study. *J Athl Train*. 2012;47(3):264-272.
110. Willardson JM. Core stability training: applications to sports conditioning programs. *J Strength Cond Res*. 2007;21(3):979-985.
111. Willems T, Witvrouw E, Delbaere K, De Cock a, De Clercq D. Relationship between gait biomechanics and inversion sprains: a prospective study of risk factors. *Gait Posture*. 2005;21(4):379-387..
112. Willems TM, De Clercq D, Delbaere K, Vanderstraeten G, De Cock a, Witvrouw E. A prospective study of gait related risk factors for exercise-related lower leg pain. *Gait Posture*. 2006;23(1):91-98.
113. Willems TM, Witvrouw E, Delbaere K, Philippaerts R, De Bourdeaudhuij I, De Clercq D. Intrinsic risk factors for inversion ankle sprains in females--a prospective study. *Scand J Med Sci Sport*. 2005;15(5):336-345.
114. Williams J. Aetiological calssification of injuries in sportsmen. *Br J Sport Med*. 1971;5(4):228-230.
115. Willson JD, Dougherty CP, Ireland ML, Davis IM. Core Stability and Its Relationship to Lower Injury. *J Am Acad Orthop Surg*. 2005;13(5):316-325.
116. Willson JD, Ireland ML, Davis I. Core strength and lower extremity alignment during single leg squats. *Med Sci Sports Exerc*. 2006;38(5):945-952.
117. Witvrouw E, Lysens R, Bellemans J, Cambier D, Vanderstraeten G. Intrinsic risk factors for the development of anterior knee pain in an athletic population. A two-year prospective study. *Am J Sports Med*. 2000;28(4):480-489.
118. Yang J, Tibbetts AS, Covassin T, Cheng G, Nayar S, Heiden E. Epidemiology of overuse and acute injuries among competitive collegiate athletes. *J Athl Train*. 2012;47(2):198-204.
119. Zazulak B, Cholewicki J, Reeves NP. Neuromuscular control of trunk stability: Clinical implications for sports injury prevention. *J Am Acad Orthop Surg*. 2008;16(9):497-505.
120. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med*. 2007;35(7):1123-1130.
121. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med*. 2007;35(3):368-373.

CHAPTER I

AN OVERVIEW OF CURRENT LITERATURE ON CORE STABILITY AND THE ASSOCIATION WITH LOWER EXTREMITY INJURIES

PART I

Is Core Stability a Risk Factor for Lower Extremity Injuries in an Athletic Population? A Systematic Review

Cedric De Blaiser[1], Philip Roosen[1], Tine Willems[1,2], Lieven Danneels[1], Luc Vanden Bossche[3], Roel De Ridder[1]

[1] *Department of Rehabilitation Sciences and Physiotherapy, Ghent University, 9000 Ghent, Belgium*
[2] *Department of Physical Therapy and Orthopedics, Ghent University, 9000 Ghent, Belgium*
[3] *Department of Physical and Rehabilitation Medicine, Ghent University Hospital, Ghent, 9000, Belgium*

Published in Physical Therapy in Sport, 2018

Full reference:
De Blaiser C, Roosen P, Willems T, Danneels L, Vanden Bossche L, De Ridder R. Is core stability a risk factor for lower extremity injuries in an athletic population? A systematic review. *Phys Ther Sport.* 2018;30:48-56. doi:10.1016/j.ptsp.2017.08.076.

Abstract

Objectives: To research and summarize the literature regarding the role of core stability as a risk factor in the development of lower extremity injuries in an athletic population.

Methods: Pubmed, Web of Science and Embase were searched in August 2016 to systematically review studies, which related core muscle functioning and core stability to lower extremity injuries.

Results: Nine articles were included in the systematic review. Various components of core stability were found to be related to lower extremity musculoskeletal injuries in healthy athletic populations. Core strength, core proprioception and neuromuscular control of the core were found to be a risk factor in the development of lower extremity injuries. However, conflicting evidence was found for core endurance as a risk factor for lower extremity injuries.

Conclusion: This systematic review provides preliminary evidence for the association between impaired core stability and the development of lower extremity injuries in healthy athletes. Deficits in various aspects of core stability were identified as potential risk factors for lower extremity injuries. As such, core stability needs to be considered when screening athletes.

Key words: Injury screening; Lumbopelvic hip complex; Trunk stability; ACL injuries; Overuse injuries

1 Introduction

Participation in sports and physical activity entails a considerable risk for musculoskeletal injury for both elite and recreational athletes.[3] Athletic injuries generally affect the lower extremity, including hip, knee, lower leg and ankle injuries.[34] A clear understanding of intrinsic risk factors, extrinsic risk factors and injury mechanisms is essential for providing successful injury prevention.[3,16,32,40] Many risk factors for lower extremity injury have already been studied thoroughly. For example, altered biomechanics including increased knee abduction angle and knee abduction moment during movement are found to be predictors for anterior cruciate ligament injuries in female athletes.[20]

In addition to these locally defined biomechanical alterations, the role of core stability related factors in the altered function of the lower extremity and the development of injuries has gained widespread attention over the last decade.[9,36,43,49] From an anatomical point of view, the musculoskeletal core of the body refers to the osseous and soft tissue structures of the spine, pelvis, and the abdomen.[5,6,27] Numerous muscles cross the spine and abdomen and contribute to core stability.[10] Core stability is generally defined as the foundation of lumbopelvic dynamic control that allows for optimal production, transfer and control of force and motion, which is transferred throughout the kinetic chain during functional movement..[8,14,17,21,28] Core stability is instantaneous and efficient functioning requires the successful integration of adequate muscular characteristics defined by strength and endurance and sensorimotor control, which relies on proprioception and neuromuscular control.[6,28,50,51] This integration is essential to guarantee sufficient core stability.[8,14,17,21]

Core stability has been implied numerous times to influence lower limb functioning.[12,19,30] Abdominal and multifidus muscles are proven to contract in anticipation of reactive forces produced by lower limb movement,[22] and preparatory motion of the trunk was demonstrated prior to asymmetric limb movement.[23] As such, core musculature could provide a stable foundation, which allows for safe and controlled movement distal to the core, and is considered as an important contributor in maintaining dynamic joint stability in the kinetic chain during locomotion.[1,4,6,,27] Furthermore, core training has been established to influence lower extremity biomechanics,[13,38] and it was found to modify and enhance sports performance.[7,26,45] Therefore, it is hypothesized that impaired core stability increases vulnerability in the development of general lower extremity injuries through uncontrolled joint displacements or accessory movements throughout the kinetic chain.[9,27]

As it is still unclear to this day whether impaired core stability could lead to injuries, researching and identifying the relationship between impaired core stability and lower extremity injuries could have important implications in the fields of injury prevention and rehabilitation. A first step towards gaining insight into this relationship is to research whether core stability can be considered as a risk factor in the development of lower extremity injuries. As of this day, an overview of the current existing evidence for core stability as a risk factor for these injuries is lacking. Therefore, the main purpose of this systematic review is to summarize the available literature on the role of core stability as a risk factor in the development of lower extremity injuries in a healthy athletic population. Secondary to this main purpose, this review will discuss the findings and explore the association between various aspects attributed to core stability and lower extremity injuries.

2 Methods

This review follows the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-analyses) guidelines. Literature search, screening, data collection and quality assessment was performed by 2 researchers independently at the University of Ghent, Belgium. Afterwards, the results were compared and differences were discussed to reach consensus. If no agreement could be reached, a third researcher would ultimately decide on the outcome.

2.1 Eligibility criteria, information sources and search strategy

Potential eligible articles were identified by consulting the electronic database Web of Science (www.webofknowledge.com/), the MEDLINE database (www.ncbi.nlm.nih.gov/pubmed/) and the Embase Library (www.embase.com) in August 2016. To answer our research question, a modified PICO – framework (Patient, Intervention, Comparison, and Outcome) was developed in which the control group (C) was not determined. Studies evaluating core stability measures as a risk factor (I) in the development of lower extremity injuries (O) in a population of healthy, athletic subjects (P) were systematically identified. The search algorithm was derived from this modified PICO - framework and was based on a combination of the following free text words, search terms and the accompanying MeSH terms for Pubmed, and EMTREE terms for Embase: (core stability OR lumbopelvic hip complex OR "lumbopelvic control" OR "lumbopelvic stability" OR "spinal stability" OR "trunk stability" OR "lumbar stability" OR "core muscles" OR "core musculature" OR "core strength" OR "core endurance" OR "core proprioception") AND (injury).

In addition, hand searching was performed by looking at relevant studies that were cited in other studies. To be eligible for inclusion, (1) studies had to report on core stability, neuromuscular control of the core/lumbopelvic complex or at least one objective measure of core stability. Any study describing measures of core stability, spinal stability, trunk stability, lumbar stability, lumbopelvic control, core musculature, core strength, core endurance or core proprioception, was accepted. Interventional studies investigating only the influence of core stability training were excluded. (2) Injuries were defined as any acute or overuse injury of the lower extremity musculoskeletal system. (3) Subjects needed to be healthy and take part in competitive sports, collegiate sports or collegiate physical education studies. (4) Articles had to be in Dutch, French or English to be included. An article was excluded when one of the four inclusion criteria was not fulfilled. Furthermore, expert opinions, case reports and reviews were also excluded.

2.2 Study selection

The selection criteria had to be fulfilled to be included in the review. Two assessors performed eligibility assessment independently in a blinded standardized manner. In the first phase, the selection criteria were only applied to the title and abstract of all potential studies. For all possible eligible studies, full texts were retrieved after first screening. In the second phase, selection was based on the full text articles. If any of the selection criteria were not fulfilled, the article was excluded from the systematic review. Disagreements were discussed and consensus was obtained for all articles included.

2.3 Data collection process and data items

The data from each included study was extracted and merged afterwards into an evidence table. Authors (1), type of study (2), sample size (3), mean age in years (4), measured aspects of core stability (5), measurement technique (6), follow-up period (7), injury type (8), injury rate (9) and main results, including effects estimates (10) were extracted from the included studies.

2.4 Quality assessment (Risk of Bias)

All included cohort studies were assessed using the Newcastle-Ottawa quality assessment scale for cohort studies (NOS, http://www.ohri.ca/programs/clinical_epidemiology/oxford.asp) in order to determine the methodological quality of the individual studies. The eight items on the NOS for cohort studies are divided into three subcategories (selection, comparability, and outcome) with a maximum attainable score of nine points, representing the highest methodological quality. Both researchers agreed on the interpretation of the different items that were scored. Item two of the selection category (1 point) and item one of the comparability category (2 points) were excluded because these items were not applicable for the included studies and were not accounted for in the end score. In order to detect articles with high risk of bias in this review, a quality score of 3/6 or 4/6 was considered as moderate quality, whereas studies scoring 5/6 or 6/6 were considered as high quality. The researchers reached a definitive score during a consensus meeting. In the end, articles with a high risk of bias were excluded from the review (methodological quality < 3/6).

Based on study design and methodological quality, each study received a level of evidence according to the 2005 classification system of the Dutch Institute for Healthcare Improvement CBO (Table 1).[33] Furthermore, a level of conclusion was determined after clustering studies with comparable methods and taking into account the level of evidence of the clustered studies and the consistency of the reported results (Table 2).[33] The levels of conclusion range from 1-4 and correspond with a high (1), moderate (2), low (3) strength of conclusion or no strength of conclusion at all (4).

Table 1 Levels of evidence for studies investigating harm, etiology or prognosis (CBO)

	Harm, etiology or prognosis
A1	Systematic reviews and meta-analyses, based on minimally 2 independent A2 studies.
A2	Prospective cohort studies with sufficient sample size and follow-up; adequately controlled for confounding factors; and precluding selective loss-to-follow-up.
B	Prospective cohort studies, but lacking the quality criteria of A2. Retrospective cohort studies and case-case control studies.
C	Non-comparative studies
D	Expert opinion

Table 2 Levels of conclusion (CBO)

	Strength of conclusion
1	1 A1 or at least 2 independent A2 studies (high strength of conclusion)
2	1 A2 or at least 2 independent B studies (moderate strength of conclusion)
3	1 B or C study or conflicting evidence (low strength of conclusion)
4	Expert opinion (no strength of conclusion)

3 Results

3.1 Study selection

The search of PubMed, Web of Science and Embase databases provided a total of 1580 citations. After deduplication, 1253 citations remained. After selection on title and abstract based on the modified – PICO criteria, fourteen full texts were withheld. Four studies were discarded based on intervention; one study was discarded based on outcome. No extra studies were identified from the reference lists using the systematic search strategy. This lead to a total of nine studies used for data extraction. The flowchart in Figure 1 shows the process of study selection and the main reasons for exclusion.

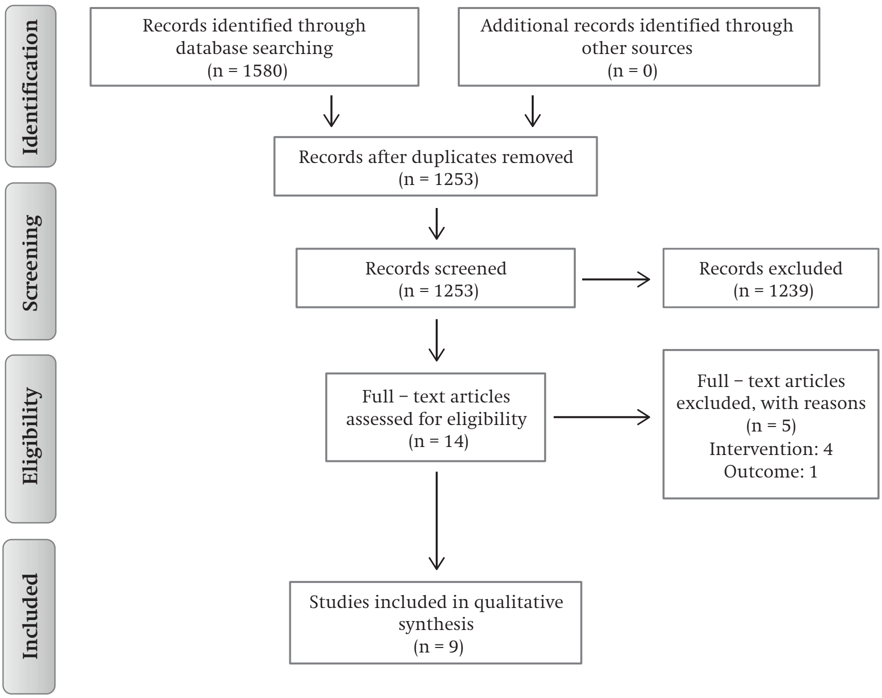


Figure 1 Flowchart of the conducted search

3.2 Study characteristics

All included studies had a prospective cohort design. Seven studies used logistic regression to determine risk factors for the development of injuries,[28,36,37,43,44,50,51] and two studies used Cox regression.[41,42]

The study population varied between 32 and 370 subjects. Three studies investigated core endurance,[28,43,44] one study investigated core strength,[36] one study investigated proprioception of the core,[51] and the four remaining studies investigated neuromuscular control of the core.[37,41,42,50]

Regarding injuries, one study reported on anterior cruciate ligament (ACL) injuries,[36] two studies reported on knee injuries including ligament/meniscal and ACL injuries,[50,51] two other studies on the development of exertional medial tibial pain (EMTP),[41,42] and the four remaining studies reported on the development of lower extremity injuries in general.[28,37,43,44] Injury follow-up period varied between six months and 10 years. Table 3 (Appendix) provides full information on the included studies.

3.3 Quality assessment (Risk of bias)

Results of quality appraisal are presented in Table 4 (Appendix). Quality of the studies was high with two studies scoring 5/6 points and moderate with six studies scoring 4/6 points and one study 3/6. The observed agreement between both raters on all items was 96,3% (52/54). Most methodological deficits were obtained on the items "representativeness of the exposed cohort" and "adequacy of follow up of cohorts".

The assessment of the level of evidence of the included studies showed a 100% agreement between both assessors during the consensus meeting. All studies are situated at level B (= Prospective cohort studies, but lacking the quality criteria of A2. Retrospective cohort studies and case-case control studies). No articles were discarded based on quality of the study. Level of conclusion is placed between brackets when describing the results.

3.4 Synthesis of results

Differences in core stability measures between injured and uninjured athletes were investigated and the evidence was summarized for which core stability measure could be considered as a risk factor for lower extremity injury in healthy athletic subjects.

Core Muscle Endurance

Three studies investigated the relationship between core muscle endurance and injuries, regardless of the injury location on the lower extremity.[28,43,44] No significant differences were found on *holding* times for anterior, posterior and lateral core muscle endurance tests in injured compared to uninjured collegiate basketball players and track athletes.[28] Furthermore, none of these measures were considered a risk factor for sustaining an injury. Two other studies also found non-significant differences in endurance times for posterior and lateral core muscle endurance tests in injured compared to uninjured collegiate football players.[43,44] However, they did find significantly lower ($P = 0.034$) endurance times for the anterior endurance test in injured athletes. Based on an injury prediction model, they also found reduced anterior core muscle endurance to be a modifiable risk factor for lower extremity injuries. In conclusion, no evidence was found for differences in performance on posterior and lateral core muscle endurance tests between injured and uninjured collegiate athletes (level of conclusion 2). Furthermore, conflicting evidence exists of anterior core muscle endurance being worse in subjects who developed injuries and there is inconsistent evidence on core muscle endurance being a risk factor for lower extremity injury (level of conclusion 2).

Core Muscle Strength

One study investigated the relationship between core muscle strength and ACL injuries.[36] Maximum absolute (Newton) and maximum relative (Newton/kg) isometric strength was measured for both trunk flexion and extension. Furthermore, trunk strength balance was calculated as the index of the ratio of absolute flexion to extension strength. They found differences in absolute strength, relative strength and strength balance in injured versus uninjured athletes. Some evidence was found for significantly lower relative flexion and extension strength ($P = 0.013$) and a significantly different strength balance ($P = 0.007$) in injured compared to uninjured male ski racers and all were identified as risk factors for ACL injuries (level of conclusion 3). Significantly lower absolute flexion and extension strength ($P = 0.009$) was found in injured compared to uninjured female ski racers and were, together with strength balance, identified as a risk factors for ACL injuries (level of conclusion 3).

Core Proprioception

Proprioception of the core, measured by active and passive repositioning sense of the lumbar spine, was investigated in only one study.[51] The difference between starting position and ending position of the trunk during an active and passive repositioning task was measured in degrees. A deviation from 0° was described as a deficit in repositioning sense. Significant deficits ($P \leq 0.05$) for active proprioceptive repositioning (APR) were found in knee injured female, but not in injured male collegiate athletes. No difference in passive proprioceptive repositioning (PPR) was found in knee injured versus uninjured athletes. Furthermore, APR was found to be a risk factor for the same injuries in female athletes. As such, there is evidence for greater deficits in APR in female athletes who developed knee injuries and evidence exists for deficits in APR of the core being a risk factor for knee injuries in female collegiate athletes (level of conclusion 3).

Neuromuscular Control of the Core

Four studies evaluated neuromuscular control of the core by evaluating movement control of the lumbopelvic region during specific tasks.[37,41,42,50] Two studies investigated uncontrolled displacement of the lumbopelvic region, measured in degrees, during a single leg drop jump landing.[41,42] Some evidence exists for an increased displacement in the transverse plane of the ipsilateral, but not contralateral hip, pelvis and trunk as a risk factor in female physical education (PE) students who developed exertional medial tibial pain (EMTP) (level of conclusion 3).

In another study, a quick force release after isometric trunk exertions against trunk flexion, extension and lateral flexion was used for calculating angular displacements of the trunk, as a measure of neuromuscular control of the trunk, in reaction to sudden unloading.[50] Total displacement of the trunk (three directions combined) after sudden force release was significantly greater ($P < 0.001$) in collegiate athletes who developed a knee injury. Based on an injury prediction model, coronal and sagittal displacements of the trunk were predictors of knee injuries in female but not male athletes, with lateral displacement of the trunk as the strongest predictor. Therefore, some evidence exists for increased trunk displacement in collegiate athletes who developed knee injuries (level of conclusion 3). Since these results are in agreement with the study of Verrelst et al.,[41] there is moderate evidence for trunk displacement during specific tasks as being a risk factor in lower extremity injuries (level of conclusion 2).

One last study examined lumbopelvic movement control by evaluating the athletes' ability to control movement of the lumbopelvic region while performing specific dynamic tests.[37] There is some evidence for the outcome of lumbopelvic movement control tests, signifying reduced movement control in dancers, as being associated with an increased risk for developing extremity injuries (level of conclusion 3).

4 Discussion

To the authors' knowledge, this is the first systematic literature review regarding the link between core stability and lower extremity injury. The hypothesis for this review was that impaired core stability is associated with lower extremity injuries and consequently, that core stability could be considered as risk factor for musculoskeletal injuries. This review revealed that various core stability related components can be considered as risk factors in the development of different types of injuries. Core strength, core proprioception and neuromuscular control of the core were found to be a risk factor in the development of lower extremity injuries. However, conflicting evidence was found for core endurance as a risk factor for lower extremity injuries. Preliminary evidence for the association between core stability and lower extremity injury has been established.

Only anterior core muscle endurance was significantly lower in injured athletes.[43,44] Furthermore, there was conflicting evidence on whether or not these measures could be considered as a risk factor for lower extremity injuries in athletes. However, a possible explanation for an increased risk for lower extremity injury is that suboptimal endurance of the core musculature results in inhibition of specific lower extremity muscles,[17,18,39] resulting in kinetic and kinematic changes during dynamic tasks, which in turn could predispose a subject to injury. Furthermore, low endurance capacity in lumbopelvic musculature was linked to the inability to avoid excessive hip adduction, knee valgus movement and femoral internal rotation during dynamic tasks.[43,48] Nevertheless, due to contradictory results in this review, it is hard to formulate a straightforward conclusion on the association between core endurance and lower extremity injury.

Core strength, rather than core endurance was hypothesized to be a better predictor for injury risk in an athletic population.[28] In the current study, some evidence was found for lower core strength measures in male and female ski racers being a risk factor in the development of ACL injuries.[36] The importance of trunk flexion to extension strength ratio has already been established in the prevention and rehabilitation of low back pain.[31] However, it has never been studied in relationship to lower extremity injuries. Significantly higher or lower strength ratios and low core strength in the study of Raschner et al.[36] were hypothetically associated with knee valgus collapse, leading to an instable, injury prone knee position during movement. This corresponds with the results of Willson et al.[49] They found that core strength was directly correlated with lower extremity alignment during weight bearing exercises, confirming the hypothesis that subjects with lower core strength were less able to resist hip internal rotation moments, resulting in excessive knee valgus movement. Since there is only one study investigating the relationship between core strength and lower extremity injury, these results cannot be compared and extrapolated to other athlete groups. However, these results do indicate an association between core strength and lower extremity injuries, which requires further research.

Decreased active core proprioception, measured in absolute degrees of movement during a repositioning task, predicted knee injury risk in female athletes.[51] For each degree increase in average repositioning error, a 2.9 - fold increase in the odds of knee injury was observed. Proprioception has been established as a primary sensory mechanism in the sensation of position and movement of joints during dynamic activities.[15] As such, proprioceptive deficits in the core may contribute to decreased active motor control of the lower extremity, which may lead to increased knee valgus angulation during movement, possibly leading to injuries.[19,20,50]

Four studies in this review investigated the influence of neuromuscular control of the core on lower extremity injuries.[37,41,42,50] Formulating an unambiguous conclusion with regards to neuromuscular control is difficult since there was variation present in measurement techniques and outcome measures in the included studies. Nevertheless, there was some evidence for displacements of the hip, pelvis and trunk during movement as predictors for lower limb overuse injury risk.[41,42] Furthermore, coronal and sagittal displacements of the trunk after sudden force release were an injury risk for knee injuries in female athletes.[50] Finally, there was limited evidence for lumbopelvic movement control as a risk factor for injuries in dancers.[37] Many athletic maneuvers, such as running, jumping, and cutting, depend on accurate sensory input and appropriate motor responses.[50] They are inherently unstable for which they require neuromuscular control throughout the kinetic chain to maintain stability. Neuromuscular control of the core is based on adequate feedback control,[50] and impaired control of the core affects neuromuscular control of adjacent joints down the kinetic chain, which may compromise dynamic stability of the knee and result in increased valgus positioning of the knee during movement, possibly resulting in injury.[29,50] Further down the kinetic chain, impaired neuromuscular control was linked to an increase in eccentric activity of lower leg musculature to control altered movement patterns. This could lead to excessive traction to the lower leg, possibly leading to exercise related, lower leg overuse injuries.[41,42]

When studying the results of this systematic review, a distinct trend can be noticed. Independent of which core stability measure is researched, the results of these studies suggest that kinematic changes occurring with core dysfunction support a pathomechanical model of femoral adduction and internal hip rotation with a valgus knee position and excessive knee valgus movement during single leg weight bearing activities. This hypothesis is being supported by current literature, in which the influence of core stability on kinetic and kinematic changes of the lower limb functioning is studied.[13,19,24,35] This is an important consideration to take into account when screening athletes in the context of injury prevention and rehabilitation.

Limitations and recommendations for future research

It is important to highlight some methodological limitations. First, it should be noted that the methodological quality of the included studies was moderate to high, with a limited level of evidence B. Secondly, there were differences seen in measurement techniques, outcome parameters and athlete populations in the studies that researched the same core stability measure. Furthermore, due to the relatively low amount of included studies, some core stability measures were discussed in only one study. Statistical pooling of results was impeded due to this low amount of studies and the substantial heterogeneity across studies for methods used for exposure assessment, data analysis and outcome measures. As such, no meta-analysis was performed.

The term core stability is commonly used, however, there is no single accepted definition and there exist many different synonyms to address this concept. Consequently, this could have led to an incomplete retrieval of suitable articles. Nevertheless, our search was deliberately kept broad and included many possible synonyms of core stability to identify as many studies of interest as possible.

More high quality prospective research in different athlete groups is definitely needed in future research. It would be interesting to see whether core stability as a whole, with inclusion of the different aspects that build core stability, could be considered as a risk factor for certain injuries. In order to do so, there should be an agreement on how these different aspects could be evaluated. As such, the assessment of core stability should be based on a comprehensive test battery where these different aspects are evaluated. In order to be clinically relevant, these tests should be valid, reliable, feasible and easy to perform. This could eliminate the need for expensive and complicated laboratory testing and could be used in the fields of athletic training, injury prevention and rehabilitation.

5 Conclusion

The results of this systematic review provide preliminary evidence for the association between impaired core stability measures and the development of lower extremity injuries in healthy athletes. Deficits in aspects of core stability such as core strength, core endurance, core proprioception and neuromuscular control of the core were identified as potential risk factors for lower extremity injuries. The results could have an important impact in the field of injury prevention and rehabilitation. When screening an athlete in the context of injury prevention, core stability measures should be considered. More high quality research is needed for further insight and future research should focus on the use of a comprehensive test battery that includes all aspects of core stability.

References

1. Akuthota V, Nadler SF. Core strengthening. *Arch Phys Med Rehabil.* 2004;85(1):86-S92.
2. Bahr R, Holme I. Risk factors for sports injuries – a methodological approach. *Br J Sports Med.* 2003;37(5):384-94.
3. Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. *Br J Sports Med.* 2005;39(6):324-329.
4. Barr KP, Griggs M, Cadby T. Lumbar stabilization: a review of core concepts and current literature, part 2. *Am J Phys Med Rehabil.* 2007;88(1):72-80.
5. Bergmark A. Stability of the lumbar spine. A study in mechanical engineering. *Acta Orthop Scand.* 1989*; 230*:1-54.
6. Borghuis J, 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.
7. Butcher SJ, Craven BR, Chilibeck PD, Spink KS, Grona SL, Sprigings EJ. The effect of trunk stability training on vertical takeoff velocity. *J Orthop Sport Phys Ther.* 2007;37(5):223-231.
8. Cholewicki J, McGill SM. Mechanical stability of the in vivo lumbar spine: Implications for injury and chronic low back pain. *Clin Biomech.* 1996;11(1):1-15.
9. Chuter VH, Janse de Jonghe XA. Proximal and distal contributions to lower extremity injury: a review of the literature. *Gait Posture.* 2012;36(1):7-15.
10. Colston MA. Core Stability, Part 1: Overview of the concept. *Int J Athl Ther Train.* 2012;17(1):8-13.
11. Cowley PM, Swensen TC. Development and reliability of two core stability field tests. *J Strength Cond Res.* 2008;22(2):619-624.
12. Dierks T a, Manal KT, Hamill J, Davis IS. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J Orthop Sports Phys Ther.* 2008;38(8):448-456.
13. Earl JE, Hoch AZ. A proximal strengthening program improves pain, function, and biomechanics in women with patellofemoral pain syndrome. *Am J Sport Med.* 2011;39(1):154-163.
14. Ebenbichler GR, Oddsson LIE, Kollmitzer J, Erim Z. Sensory-motor control of the lower back: Implications for rehabilitation. *Med Sci Sports Exerc.* 2001;33(11):1889-1898.
15. Gandevia SC, McCloskey DI, Burke D. Kinaesthetic signals and muscle contraction. *Trends Neurosci.* 1992;15(2):62-65.
16. Gissane C, White J, Kerr K, Jennings D. An operational model to investigate contact sports injuries. *Med Sci Sports Exerc.* 2001;33(12):1999-2003.
17. Hammill RR, Beazell JR, Hart JM. Neuromuscular Consequences of Low Back Pain and Core Dysfunction. *Clin Sports Med.* 2008;27(3):449-462.
18. Hart JM, Fritz JM, Kerrigan DC, Saliba EN, Gansneder BM, Ingersoll CD. Reduced quadriceps activation after lumbar paraspinal fatiguing exercise. *J Athl Train.* 2006;41(1):79-86.
19. Hewett TE, Ford KR, Myer GD. Anterior cruciate ligament injuries in female athletes: Part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. *Am J Sports Med.* 2006; 34(3):490-498.
20. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med.* 2005;33(4):492-501.
21. Hibbs AE, Thompson KG, French D, Wrigley A, Spears I. Optimizing performance by improving core stability and core strength. *Sport Med.* 2008;38(12):995-1008.
22. Hodges PW, Richardson CA. Contraction of the abdominal muscles associated with movement of the lower limb. *Phys Ther.* 1997;77(2):132-142.
23. Hodges PW, Cresswell AG, Daggfeldt K, Thorstensson A. Three dimensional preparatory trunk motion precedes asymmetrical upper limb movement. *Gait Posture.* 2000;11(2):92-101.
24. Ireland ML. Anterior cruciate ligament injury in female athletes: epidemiology. *J of Athl Train.* 1999;34(2):150-154.
25. Ireland ML, Willson JD, Ballantyne BT, Davis IM. Hip Strength in Females With and Without. *J Orthop Sport Phys Ther.* 2003.
26. Jamison ST, McNeilan RJ, Young GS, Givens DL, Best TM, Chaudhari AM. Randomized controlled trial of the effects of a trunk stabilization program on trunk control and knee loading. *Med Sci Sports Exerc. 2012;44*(10):1924-1934.

27. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-198.
28. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc.* 2004;36(6):926-934.
29. Markolf KL, Burchfield DM, Shapiro NM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* 1995;13(6):930-935.
30. McGill S. Core training: Evidence translating to better performance and injury prevention. *Strength Cond J.* 2010;32(3):33-46.
31. McGill SM. 2002. Low Back Disorders: Evidence-Based prevention and rehabilitation. (2nd ed.). Human Kinetics.
32. Meeuwisse WH. Assessing causation in sport injury: a multifactorial model. *Clin J Sport Med.* 1994;4(3):166-170.
33. Meeus M, Gebruers N. Health Literacy. From reference to review. 1st ed. Leuven (Belgium)/Den Haag (The Netherlands): Acco; 2016.
34. Murphy DF, Connolly DAJ, Beynnon BD. Risk factors for lower extremity injury: a review of the literature. *Br J Sports Med.* 2003;37(1):13-29.
35. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res.* 2005;19(1):51-60.
36. Raschner C, Platzner H, Patterson C, Werner I, Huber R. Hildebrandt C. The relationship between ACL injuries and physical fitness in young competitive ski racers: a 10-year longitudinal study. *Br J Sports Med.* 2012;46(15):1065-1071.
37. Roussel NA, Nijs J, Mottram S, Van Moorsel A, Truijen S, Stassijns G. Altered lumbopelvic movement control but not generalized joint hypermobility is associated with increased injury in dancers. A prospective study. *Man Ther.* 2009;14(6):630-635.
38. Sato K, Mokha M. Does core strength training influence running kinetics, lower-extremity stability, and 5000-M performance in runners? *J Strength Cond Res.* 2009;23(1):133-140.
39. Suter E, Lindsay D. Back muscle fatigability is associated with knee extensor inhibition in subjects with low back pain. *Spine (Phila Pa 1976).* 2001;26(16):E361-6.
40. van Mechelen W, Hlobil H, Kemper HC. Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Med.* 1992;14(2):82-99.
41. Verrelst R, De Clercq D, Vanrenterghem J, Willems T, Palmans T, Witvrouw E. The role of proximal dynamic joint stability in the development of exertional medial tibial pain: A prospective study. *Br J Sports Med.* 2014;48(5):388-393.
42. Verrelst R, De Clerq D, Willems TM, Roosen P, Witvrouw E. Contralateral risk factors associated with exertional medial tibial pain in women. *Med Sci Sports Exerc.* 2014;46(8):1546-1553.
43. Wilkerson GB, Colston MA. A refined prediction model for core and lower extremity sprains and strains among collegiate football players. *J Athl Train.* 2015;50(6):643-650.
44. Wilkerson GB, Giles JL, Seibel DK. Prediction of core and lower extremity strains and sprains in collegiate football players: A preliminary study. *J Athl Train.* 2012;47(3):264-272.
45. Willardson JM. Core stability training: applications to sports conditioning programs. *J Strength Cond Res.* 2007;21(3):979-985.
46. Willems TM, De Clercq D, Delbaere K, Vanderstraeten G, De Cock a, Witvrouw E. A prospective study of gait related risk factors for exercise-related lower leg pain. *Gait Posture.* 2006;23(1):91-98.
47. Willems TM, Witvrouw E, De Cock A, De Clerq D. Gait-related risk factors for exercise-related-lower-leg pain during shod running. *Med Sci Sports Exerc.* 2007;39(2):330-339.
48. Willson JD, Dougherty CP, Ireland ML, Davis IM. Core Stability and Its Relationship to Lower Injury. *J Am Acad Orthop Surg.* 2005.
49. Willson JD, Ireland ML, Davis I. Core strength and lower extremity alignment during single leg squats. *Med Sci Sports Exerc.* 2006;38(5):945-952.
50. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med.* 2007a;35(7):1123-1130.
51. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med.* 2007b;35(3):368-373.

Appendix

Table 3 Summary of the evidence for the association between core stability and lower leg injuries

Authors	Type of study	Sample size	Mean age in years (±SD)	Measured aspect of core stability	Measurement technique
Leetun et al. (2004)	Prospective study	140 (80 ♂, 60 ♀) collegiate basketball and track athletes	♀ (19.1 ± 1.37) ; ♂ (19.0 ± 0.90)	Core muscle endurance	Hold times (s) of: -PCME: Biering-Sørensen test -LCME: Side bridging test -ACME: Flexor endurance test
Raschner et al. (2012)	Prospective study	370 (195 ♂, 175 ♀) competitive ski racers	/	Core muscle strength	-Maximal isometric core strength parameters measured with a force transducer -Measured parameters: ABS FF, ABS EF, REL FF, REL EF, FLE:EXT R
Roussel et al. (2009)	Prospective study	32 (6 ♂, 26 ♀) competitive dancers	(20 ± 2)	Neuromuscular control of the core	-Lumbopelvic movement changes during ASLR; BKFO; KLAT measured with pressure biofeedback -Lumbopelvic movement changes in SB measured with visual inspection
Verrelst et al. (2013)	Prospective study	86 ♀ physical education students	♀ (19.38 ± 0.85)	Neuromuscular control of the core	Kinematic measures of trunk/ lumbopelvic hip complex measured during a single leg drop jump landing
Verrelst et al. (2015)	Prospective study	81 ♀ physical education students	Uninjured ♀ (19.33 ± 0.81) / Injured ♀ (19.27 ± 0.90	Neuromuscular control of the core	Kinematic measures of trunk/ lumbopelvic hip complex measured during a single leg drop jump landing

Follow-up period	Injury type	Injury rate (n)	Main results*
1 playing season	General lower extremity injuries	48 (34%) (13 males, 28 females)	a) Lower holding times on all endurance tests in injured subjects compared to uninjured subjects (P = 0.22 – 0.43). b) Lateral core muscle endurance is not a risk factor for lower extremity injuries, OR = 1.01 (0.99, 1.02) (P = 0.46). Posterior core muscle endurance is not a risk factor for lower extremity injuries, OR = 1.00 (0.99, 1.01) (P = 0.44).
Prospective study for a 10 year follow-up period	ACL injuries	57 (15%) (18 males, 39 females)	a) FLE:EXT R was different (P = 0.007) and REL FF/EF are lower (P = 0.013) for the injured male subjects compared to uninjured subjects. ABS FF/EF is lower (P = 0.009) for the injured female subjects compared to uninjured subjects. b) Reduced core strength is predictive for ACL injuries. FLE:EXT R, OR = 0.24 (0.10, 0.57) (P = 0.001) and REL FF/EF, OR = 0.45 (0.21, 0.95) (P = 0.035) are risk factors in male subjects. FLE:EXT R, OR = 0.54 (0.31, 0.94) (P = 0.028) and ABS FF/EF, OR = 0.26 (0.13, 0.51) (P < 0.001) are risk factors in female subjects.
6 – month period	General lower extremity injuries	19 (59%)	b) Results of KLAT, OR = 0.59 (0.38, 0.9) (P = 0.015) and SB, OR = 8.79 (1.24, 62.09) (P = 0.029) are predictive of lower extremity injury.
1-2 academic years (depending on the year of enrollment)	Exertional medial tibial pain (EMTP)	22 (26%)	b) Increased ROM values of ipsilateral hip and thorax in the transvers plane are risk factors in developing EMTP, HR = 1.093 – 1.150 (P = 0.010 – 0.045).
1-2 academic years (depending on the year of enrollment)	Exertional medial tibial pain (EMTP)	11 (14%)	a) No significant differences found in contralateral kinematic measures of thorax/lumbopelvic hip complex in injured compared to uninjured subjects (P = 0.096 – 0.796). b) No risk factors were determined from these contralateral kinematic measures

1

Table 3 Continued

Authors	Type of study	Sample size	Mean age in years (±SD)	Measured aspect of core stability	Measurement technique
Wilkerson et al. (2012)	Prospective study	83 ♂ collegiate football players	♂ (20.0 ± 1.5)	Core muscle endurance	Hold times (s) of: -PCME: Biering-Sørensen test -LCME: Side bridging test -ACME: Flexor endurance test
Wilkerson et al. (2015)	Prospective study	152 ♂ collegiate football players	♂ (19.7 ± 1.5)	Core muscle endurance	Hold times (s) of: -PCME: Biering-Sørensen test -LCME: Side bridging test -ACME: Flexor endurance test
Zazulak et al. (2007)a	Prospective study	277 (137 ♂, 140 ♀) collegiate athletes	♀ (19.4 ± 1.0) ; ♂ (19.3 ± 1.8)	Neuromuscular control of the core	Displacement of the trunk after sudden force release, measured in the amount of movement in the sagittal and coronal plane
Zazulak et al. (2007)b	Prospective study	277 (137 ♂, 140 ♀) collegiate athletes	♀ (19.4 ± 1.0) ; ♂ (19.3 ± 1.8)	Core proprioception	Active and passive repositioning of the trunk, measured in absolute degrees of movement

*Main results: a) Differences between the injured and uninjured subjects are presented with the significant level set at $P < 0.05$. b) Risk estimates (Odds Ratio/Hazard Ratio) are presented with corresponding 95% confidence interval and corresponding P – value (if sufficient data were available from the original publication).

PCME: Posterior core muscle endurance; LCME: Lateral core muscle endurance; ACME: Anterior core muscle endurance; ABS FF: Absolute flexion force; ABS EF: Absolute extension force; REL FF: Relative flexion force; REL EF: Relative extension force; FLE:EXT R: Ratio of absolute flexion to extension ratio; ASLR: Active straight leg raise; BKFO: Bent knee fall out; KLAT: Knee lift abdominal test; SB: Standing bow

Follow-up period	Injury type	Injury rate (n)	Main results*
1 playing season	General lower extremity injuries	32 (39%)	a) Significant lower anterior core muscle endurance in injured subjects compared to uninjured uninjured subjects (P = 0.034). b) Poor anterior core muscle endurance is a modifiable risk factor in the development of lower extremity injuries, OR = 4.17 (1.52, 11.45) (P = 0.004).
1-3 playing seasons (depending on the year of initial participation)	General lower extremity injuries	132 (87%)	b) Poor anterior core muscle endurance is a modifiable risk factor in the development of lower extremity injuries, OR = 2.27 (1.47, 3.67) (P = 0.001)
3 years of collegiate athletics	Knee injury/ knee ligament or meniscal injuries/ ACL injuries	25 (9%) (14 males, 11 females)	a) Displacements of the trunk after sudden force release are greater in injured subjects (P < 0.001 − 0.05). b) Coronal and sagittal displacements of the trunk after sudden force release are predictors for knee injury in female, OR = 1.35 − 2.33 (P = 0.024 − 0.084), but not male subjects. Increased lateral trunk displacement is the strongest predictor of knee injuries, OR = 2.33 (P = 0.024).
3 years of collegiate athletics	Knee injury/ knee ligament or meniscal injuries/ ACL injuries	25 (9%) (14 males, 11 females)	a) Significant deficits (P ≤ 0.05) for active proprioceptive repositioning (APR) in knee injured female, but not in male subjects. b) Impaired proprioception of the core, measured by active proprioceptive repositioning of the trunk, predicts knee injury risk in female, OR = 2.91 (P = 0.005), but not male subjects.

1

Table 4 Quality assessment of cohort studies using a modified Newcastle – Ottawa scale

Study	Selection				Comparability	Outcome				
Cohort	**1**	**2**	**3**	**4**	**5**	**7**	**8**	**9**	**Total**	**LOE**
Leetun et al. (2004)	1	/	0	1	/	1	1	1	5/6 (83%)	B
Raschner et al. (2012)	0	/	1	1	/	1	1	0	4/6 (67%)	B
Roussel et al. (2009)	0	/	1	0	/	1	0	1	3/6 (50%)	B
Verrelst et al. (2013)	0	/	1	1	/	1	1	1	5/6 (83%)	B
Verrelst et al. (2015)	0	/	1	1	/	1	1	0	4/6 (67%)	B
Wilkerson et al. (2012)	0	/	1	0	/	1	1	1	4/6 (67%)	B
Wilkerson et al. (2015)	0	/	1	0	/	1	1	1	4/6 (67%)	B
Zazulak et al. (2007a)	1	/	0	1	/	1	1	0	4/6 (67%)	B
Zazulak et al. (2007b)	1	/	0	1	/	1	1	0	4/6 (67%)	B

LOE: Level of Evidence, / = not applicable

CHAPTER II

RELIABILITY AND VALIDITY OF CLINICAL ASSESSMENT TOOLS TO EVALUATE CORE STABILITY

PART I

Evaluating Abdominal Core Muscle Fatigue: Assessment of the Validity and Reliability of the Prone Bridging Test

Cedric De Blaiser[1], Roel De Ridder[1], Tine Willems[1,2], Lieven Danneels[1], Luc Vanden Bossche[3], Tanneke Palmans[1], Philip Roosen[1]

[1] *Department of Rehabilitation Sciences and Physiotherapy, Ghent University, 9000 Ghent, Belgium*
[2] *Department of Physical Therapy and Orthopedics, Ghent University, 9000 Ghent, Belgium*
[3] *Department of Physical and Rehabilitation Medicine, Ghent University Hospital, Ghent, 9000, Belgium*

Published in Scandinavian Journal of Medicine & Science in Sports, 2018

Full reference:
De Blaiser C, De Ridder R, Willems T, et al. Evaluating abdominal core muscle fatigue: Assessment of the validity and reliability of the prone bridging test. *Scand J Med Sci Sport*. 2018;28(2):391-399. doi:10.1111/sms.12919

Abstract

Objectives: The aims of present study were to research the amplitude and median frequency characteristics of selected abdominal, back and hip muscles of healthy subjects during a prone bridging endurance test, based on surface electromyography (sEMG), (1) to determine if the prone bridging test is a valid field test to measure abdominal muscle fatigue, and (2) to evaluate if the current method of administrating the prone bridging test is reliable.

Methods: Thirty healthy subjects participated in this experiment. The sEMG activity of seven abdominal, back and hip muscles was bilaterally measured. Normalized median frequencies were computed from the EMG power spectra. The prone bridging tests were repeated on separate days to evaluate inter- and intra-tester reliability.

Results: Significant differences in normalized median frequency slope (NMF_{slope}) values between several abdominal, back and hip muscles could be demonstrated. Moderate to high correlation coefficients were shown between NMF_{slope} values and endurance time. Multiple backward linear regression revealed that the test endurance time could only be significantly predicted by the NMF_{slope} of the rectus abdominis. Statistical analysis showed excellent reliability (ICC = 0.87-0.89) for intra –and inter-tester reliability based on prone bridging holding times.

Conclusion: The findings of the present study support the validity and reliability of the prone bridging test for evaluating abdominal muscle fatigue.

Keywords: Muscle endurance; Core stability; Screening; Injury prevention; Field test; Planking

1 Introduction

Numerous clinical tests have been suggested to help evaluate and identify deficiencies in core muscle performance.[5,24,31] Many of these tests are isometric trunk holding tests, commonly used to measure the endurance capacity and fatigability of the core muscles.[12,21,30] Evaluating core muscle capacity is clinically relevant since it is considered to be related to low back pain,[1,21] musculoskeletal injury risk,[24,41] and even athletic function.[22,25] Typically, these tests require minimal, inexpensive equipment, and are safe and simple to perform in a clinical environment where performance and endurance capacity is evaluated by recording the maximum time a subject can maintain a correct test position.[17] The prone bridging test, an isometric holding test in prone position, is commonly used to purportedly measure the endurance capacity of the abdominal core muscles.[2,16,39,40] It has been theorized to be a functional test for abdominal core muscle endurance, since endurance is measured during an activity requiring simultaneous activation of the anterior core musculature.[6]

A frequent issue encountered in studies using such clinical screening measures is the insufficient validity and reliability of these tests.[17,18] Validity in general is defined as the degree to which a meaningful interpretation can be inferred from a measure or test whereas reliability refers to the consistency or repeatability of a measure or test.[37] Validity and reliability of certain isometric trunk holding tests have already been discussed and established. The frequently used Biering-Sørensen test, for example, has been deemed a valid and reliable test to measure back muscle endurance.[12,17,34] However, reliability and especially validity of the prone bridging endurance test has not yet been researched thoroughly. Studies researching the reliability of the prone bridging test report conflicting results. Low, moderate as well as excellent reliability values have all been reported.[13,15,33,40] These diverse outcomes might be the result of methodological limitations of these particular studies such as a limited recovery time between test repetitions or the use of video camera footage to evaluate reliability.[15,33,40] Furthermore, differences in testing protocol for the prone bridging test, such as varying termination criteria for the test, could also result in discrepant reliability results.

On the other hand, research into the validity of the prone bridging test is sparse and often applied to modified versions of this test. Tong et al.,[36] for example, investigated the validity of a sport specific, dynamic version of the prone bridging test where different levels of difficulty were added to the test in order to target a specific athletic group. Furthermore, research on the validity of the prone bridging test, using electromyography (EMG) as reference method, is often based on the evaluation of parameters that do not specifically represent muscle fatigue. Schellenberg et al.,[33] for example, only investigated relative muscle activation during a prone bridging test in order to ascertain validity. However, electromyographic (EMG) spectrum analysis has been generally used to monitor the development of localized muscle fatigue, since fatigue causes a decrease of the frequency content of the EMG signal, usually described as a decline of the median frequency parameters of the EMG spectrum.[4,12,27] Furthermore, it has been proven that local muscle endurance is associated with fatigue-based changes in EMG properties.[3]

The aims of the present study therefore were to investigate both the amplitude and median frequency characteristics of the surface electromyographic (sEMG) signals recorded from different abdominal, back and hip muscles of healthy subjects during the prone bridging endurance test, (1) to determine whether the prone bridging endurance test based on visual inspection and tactile feedback is a valid test for specifically measuring abdominal muscle fatigue and (2) to research if this current method of administrating the prone bridging test is reliable.

2 Materials and methods

2.1 Participants

A total of 30 healthy subjects voluntarily participated in this study. Measurement data from 1 subject were discarded due to drop out on account of an injury between test moments. The eventual group consisted of 15 women and 14 men (mean age 25.5 ± 2.1 years; mean height 170 ± 7.9 cm; mean weight 65.6 ± 13.1 kg; mean BMI 22.5 ± 3.2 kg/m^2). All participants were over the age of 18, had no prior history of low back pain, had no known pathology, and were habitually active. The subjects also needed to be able to assume the correct test position. The local University Hospital's ethics committee approved the study protocol. Subjects gave their written informed consent prior to participation.

2.2 Study design

The prone bridging tests were supervised by 2 examiners. They were both extensively trained to ensure standardized testing procedures.

Validation and reliability of the prone bridging test were conducted in separate phases. The first phase examined the validity of the prone bridging test and consisted of analyzing the sEMG activity of 3 abdominal, 2 back and 2 hip muscles during the prone bridging test. Only examiner 1 evaluated this trial. The second phase evaluated the reliability of the prone bridging test and consisted of comparing the results of the tests executed on two separate days. On day 1, two prone bridging tests were executed without the use of sEMG. On day 2, one week later, the same protocol was repeated. A randomization protocol was used to determine whether the first trial was evaluated by either examiner 1 or 2. Between the two tests each day, a resting period of 1 hour was given to each subject. The same warm-up protocol was utilized for each test. All the subjects refrained from participating in strenuous physical activity for at least one day before the test days.

2.3 Prone bridging protocol

Figure 1 shows the correct position during the prone bridging test. The subjects had to maintain a prone position propped on the forearms with shoulders and elbows in 90° flexion with both arms shoulder-width apart. Both feet were placed at hip-width. Forearms needed to remain in a neutral position, halfway between pronation and supination with the fists clenched. The pelvis was raised from the floor. A straight line was formed between the most lateral point of the acromion, the greater trochanter and the lateral malleolus. The subjects were instructed to look downward at a visual fixation point during the test in order to maintain a neutral position of the head. During the test, the examiner instructed the subjects to maintain this position as long as possible until fatigue or pain prevented the continuation of the test. The subjects were allowed a pre-test familiarization attempt. During the performance, the examiner gave the same verbal instructions and standardized encouragement for every subject. Tactile feedback to correct the position was given either at the anterior superior iliac spine (ASIS) or posterior superior iliac spine (PSIS) when the pelvis respectively lowered to the ground or elevated itself from the ground. When the corrected position could not be held for 2 seconds, the subject was instructed to halt the test. The endurance time was recorded manually from the moment when the correct position was assumed until the test was terminated by the examiner or subject. Instructions on the correct position, test administration and feedback during the test were the same for each test.

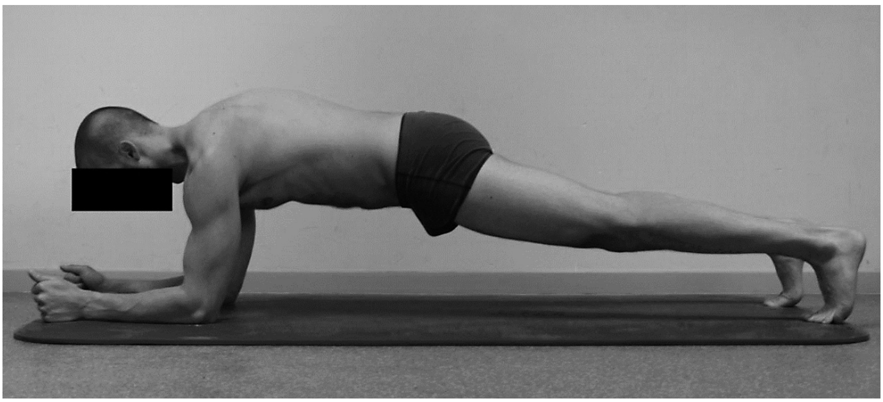


Figure 1 Prone bridging test position

2.4 Equipment, data registration and signal processing

The EMG signals were recorded with a 16-channel surface EMG system (MyoSystem 1400, Noraxon USA Inc., Scottsdale, AZ). All raw EMG signals were analogue band-pass-filtered between 10 and 500 Hz, amplified (common mode rejection ratio >100 dB, overall gain 1000, noise <1μv RMS), analogue-to-digital converted (12-bit) at a sampling rate of 1000 Hz. Fourteen pairs of circular surface electrodes with an electrical surface contact of 1 cm^2 (Ag/AgCl, BlueSensor P, Ambu A/S, Denmark) were bilaterally attached on selected abdominal, back and hip muscle sites, which are described below. The electrodes were placed within the borders of the muscles, parallel to the muscle fibers and with an interelectrode distance of 25 mm. Before attaching the electrodes, the skin was shaven, scrubbed and cleaned with alcohol in order to decrease impedance of the skin-electrode interface. Following electrode locations were used: rectus abdominis (RA) (two cm lateral from the umbilicus),[34] external oblique (EO) (parallel to the line extending from the most inferior point of the costal margin to the opposite pubic tubercle, 14 cm lateral to the median line, lower 1 cm above umbilicus, 1 cm or more above iliac crest),[7] internal oblique (IO) (2cm lower the most prominent point of the ASIS, just medial and superior to the inguinal ligament),[7] rectus femoris (RF) (halfway between ASIS and patella),[19] iliocostalis lumborum pars thoracis (ILT) (midway between the lateral palpable border of the erector spinae and a vertical line through the PSIS),[26] multifidus (MF) (two cm lateral of the spine at the height of PSIS)[14] and the biceps femoris (BF) (halfway between ischial tuberosity and the lateral fibular epicondyle)[19]. Cables were attached and taped to the body in order to guarantee minimal interference and prevent unintentional removal of the electrodes. Preparation of the skin and placement of the electrodes was performed by the same examiner.

A 5-second maximum voluntary isometric contraction (MVIC) of all these muscles was performed against a manual resistance for 3 repetitions. A resting period of 15 seconds was given between each repetition. Standardized verbal encouragement was provided during the testing. Testing positions for the administration of the MVIC are described by Cholewicki et al.[10] and Konrad.[23] EMG signal registration and processing was done in Noraxon's Myoresearch v3.6 (Noraxon USA Inc., Scottsdale, AZ) and Matlab R2015a (MathWorks USA Inc., Natick, MA).

2.5 Data analysis

The raw data of the EMG signals were ECG reducted, full-wave rectified and smoothed using a root mean square (RMS) with a moving average window of 100ms. The mean amplitude during the MVIC trials was determined for each individual muscle, and subsequently, the mean of the three MVIC trials was calculated. Normalization of the EMG amplitude data, collected from each muscle during the prone bridging test, was executed by expressing the mean amplitude of the EMG signal during the length of the test as a percentage of the mean MVIC value of the corresponding muscle. Normalization of the EMG amplitude data allowed for comparison of the relative EMG activity between the different muscles during the prone bridging test. Pooled data from all subjects gave an average percentage of the normalized EMG amplitude of each muscle.

The normalized median frequency slope (NMF_{slope}) of the EMG signal of every muscle during the prone bridging test was calculated. Each recorded EMG signal during the prone bridging test was divided in intervals of 1 second. The median frequency of the EMG power spectrum was calculated in each 1 second interval with fast Fourier transforms (FFT) also using both Noraxon's Myoresearch and Matlab. The median frequency was defined as the frequency that divides the power spectrum into two equal areas. Median frequency slope was used to represent muscle fatigue since fatigue causes a decrease of the frequency content of the EMG signal, often described as a decline of the median frequency parameters of the EMG power spectrum.[12,28] Therefore, linear regression analyses were performed on the calculated median frequencies of the EMG signal of each prone bridging test as a function of time. The initial median frequency (MF_{init}) was determined as the intercept of the regression line. The median frequency slope (MF_{slope}) was defined as the slope of the regression line. Because EMG parameters can be affected by differences in subcutaneous tissue layers (between muscle locations of the same subject), the MF_{slope} was automatically normalized with respect to the intercept of the regression with the formula MFslopeMFinit x 100.[12] We thus further refer to the NMF_{slope}.

2.6 Statistical analyses

Validity

The following methods were used to determine and reinforce the validity for the prone bridging test based on sEMG amplitude and median frequency characteristics. In a first step towards validating the test, a non-parametric Friedman ANOVA test was used to examine differences in normalized EMG amplitude between the different muscles. Post hoc Wilcoxon signed rank tests with Bonferroni correction were performed to compare the means of the normalized EMG amplitude data of the different muscles to investigate which muscles are relatively more active during the prone bridging test. Next, a one-way repeated measures ANOVA design was conducted to investigate the main effect of the independent variable muscle on the dependent variable NMF_{slope} and post hoc pair-wise comparisons were made with Bonferroni correction to compare the mean NMF_{slopes} of each muscle with each other. Pearson correlation coefficients were calculated between NMF_{slopes} of the different muscles and the endurance time to evaluate their relationship. The interpretation of the correlation coefficients (*r*) was set in accordance with Cohen[11] (1988): low = 0.10-0.30, moderate = 0.30-0.50 and high >

0.50. The same ranges are applicable for negative correlation coefficients.[11] Finally, multiple backward linear regression analyses were performed to assess which NMF_{slope} best predicted the endurance time. Statistical significance for all tests was accepted at the 5% level. All statistical analyses were conducted with the statistical software package SPSS v23.0 (SPSS Inc., Chicago, IL, USA).

Reliability

Both intra-tester (tester 1, between 2 days) and inter-tester reliability (between tester 1 and 2, the same day) based on the endurance times of the prone bridging test were assessed. Intraclass correlation coefficients (ICC) with 95% confidence intervals (CI) were used to assess reliability by utilizing a two-way random effects model with single measure reliability (ICC (2,1)). The interpretation of the ICC was in accordance with Cicchetti & Sparrow[9] with low reliability identified as a value < 0.40, moderate reliability 0.40 – 0.59, good reliability 0.60 – 0.75 and excellent reliability > 0.75. The standard error of measurement (SEM), a reliability index that indicates the extent to which a score varies on repeated measurements, was calculated (SEM=SD 1−ICC).

3 Results

3.1 Validity

Differences in normalized EMG amplitude between muscles

A non-parametric Friedman ANOVA test indicated a significant difference in normalized EMG amplitude between the different muscles during the prone bridging test (χ^2 (6) = 117.47, $p < 0.001$). Post hoc Wilcoxon signed rank tests with Bonferroni correction (and a significance level established at the 0.0023 level) demonstrated significantly higher activated abdominal core muscles (RA, OE and OI, ranging from 58.32 % to 63.56 % of MVIC) compared to the back and hip muscles (ILT, MF, RF and BF, ranging from 11.7 % to 33.93 % of MVIC). Furthermore, the RF was significantly more activated than the ILT, MF and BF, but still significantly less activated than the abdominal muscles. The normalized EMG amplitude data is presented in Figure 2.

Differences in NMF_{slope} values between muscles

Sphericity was not assumed in the one-way repeated measures ANOVA but after a Huynh-Feldt correction, the main effect of the independent variable muscle demonstrated a significant effect on the dependent variable NMF_{slope} ($p < 0.001$). The NMF_{slope} values with standard deviations for the abdominal, back and hip muscles are shown in Figure 3. Significant differences between the NMF_{slope} values of these muscles after pair-wise comparison with Bonferroni correction are presented as well. The RA showed a significantly greater NMFslope ($p < 0.05$) than all muscles, except for the ILT. The lowest NMFslope is presented by the BF, but differs only significantly from the RA and EO ($p < 0.05$). The same can be said from the RF. There was no significant difference between the 2 back muscles, the ILT and MF ($p > 0.05$). Furthermore, both EO and IO were not significantly different from each other as well ($p > 0.05$).

Correlation coefficients of NMF_{slope} values and endurance time

The Pearson correlation coefficients (*r*) between the endurance time and the NMFslope of the muscles are shown in Table 1. Significant correlation coefficient for the RA, EO, IO and ILT could be demonstrated with *r* ranging from 0.410 to 0.591. IO had the largest correlation coefficient ($r = 0.591$) which was high according to Cohen[11] (1988), however it did not differ greatly from the high correlation coefficient of the RA ($r = 0.587$). The moderate correlation coefficients of the EO ($r = 0.410$) and ILT ($r = 0.425$) were also significant. The RF ($r = 0.081$) and BF ($r = -0.046$) demonstrated low, non-significant correlation coefficients that were lower than the abdominal and back muscles.

2

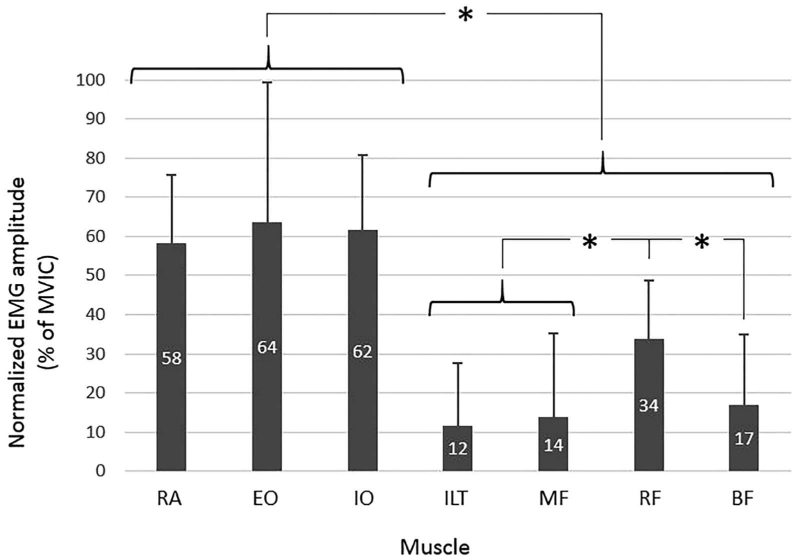


Figure 2 Normalized EMG amplitude of the 7 abdominal, back and hip muscles obtained during a prone bridging test.

(RA = rectus abdominis, EO = external oblique, IO = internal oblique, ILT = iliocostalis lumborum pars thoracis, MF = multifidus, RF = rectus femoris, BF = biceps femoris. The error bars indicate the standard deviations).
* = Significant differences after post hoc Wilcoxon signed rank tests with Bonferroni correction ($p < 0.0023$)

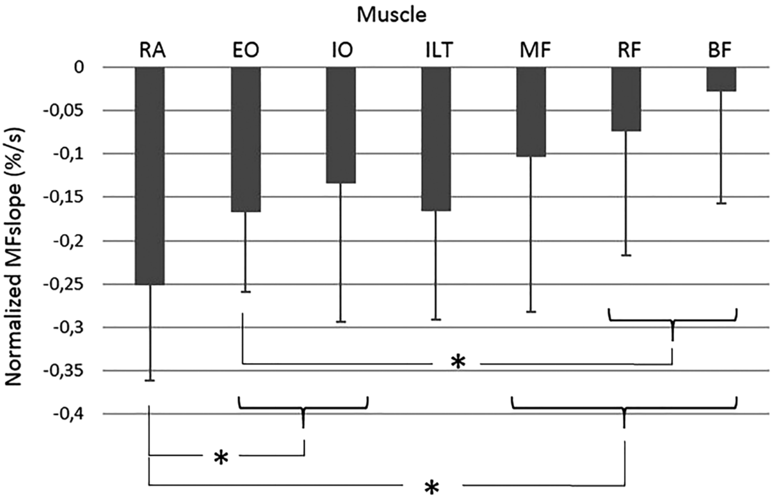


Figure 3 NMFslope values (%/s) of the 7 abdominal, back and hip muscles obtained during a prone bridging test.

(RA = rectus abdominis, EO = external oblique, IO = internal oblique, ILT = iliocostalis lumborum pars thoracis, MF = multifidus, RF = rectus femoris, BF = biceps femoris. The error bars indicate the standard deviations).
* = Significant differences after post hoc pair-wise comparison with Bonferroni correction ($p < 0.05$)

Table 1 Pearson correlation coefficients (r) between NMFslope values and endurance time

Muscle	RA	EO	IO	ILT	MF	RF	BF
Pearson correlation coefficient (r)	0.587**	0.410*	0.591**	0.425*	0.196	0.081	-0.046

RA = rectus abdominis, EO = external oblique, IO = internal oblique, ILT = iliocostalis lumborum pars thoracis, MF = multifidus, RF = rectus femoris, BF = biceps femoris. *significant correlation at the 5% level. **significant correlation at the 1% level

Which muscles predict test endurance time?

Multiple backward linear regression analyses, with all NMF_{slope} values as independent variables and endurance time as dependent variable, revealed that endurance time could only be significantly predicted by the NMF_{slope} of the RA ($p < 0.05$). The resulting regression equation could be written as:
endurance time = 194.914 + 269.611 x NMF_{slope} *of the RA (Adjusted* $R^2 = 0.261$*).*

3.2 Reliability

The overall mean of all endurance times was 140.5 ± 59.7 s. The minimum recorded endurance time was 42.9 s and the maximum recorded endurance time was 270.7 s. Physical discomfort at test termination was pain (17,2%), fatigue (81%) or other (1,8%). Body regions where this was felt the most were the arms/shoulders (15,5%), abdominal region (60.3%), back (17,2%), legs (6%) or other (1%).

Intra-tester and inter-tester reliability assessment for the prone bridging test was conducted with 29 subjects. Two raters evaluated the prone bridging tests without the use of sEMG. The endurance times of tester 1, day 1 (mean time: 149.7 ± 69.1 s), tester 1, day 2 (mean time: 146.8 ± 53.2 s) and tester 2, day 2 (mean time: 138.8 ± 60.4 s) were used to calculate reliability. Excellent ICC-values for both intra-tester and inter-tester reliability were obtained. Table 2 shows an excellent intra-tester reliability with ICC = 0.89 with a SEM of 20.9 s and an excellent inter-tester reliability with ICC = 0.87 and a SEM of 20.75 s.

Table 2 Intra-tester and inter-tester reliability of the prone bridging test

	N	(ICC 2,1)	95% CI	SEM (s)
Intra-tester (tester 1)	29	0.89	0.78 - 0.95	20.9
Inter-tester (tester 1 & 2)	29	0.87	0.73 - 0.93	20.75

N = number of subjects; CI = Confidence Interval; SEM = Standard Error of Measurement

2

4 Discussion

The prone bridging test has been frequently used to evaluate core stability, and more specifically abdominal core muscle endurance in clinical settings.[2,16,39,40] However, no consistent data with regard to validity and reliability of this test exist to this day. Therefore, the purpose of this present study was to examine, by means of researching the validity and reliability, whether a prone bridging test until failure with visual evaluation by an examiner and with tactile feedback to adjust the subject when the correct position was lost, can indeed be administered to specifically evaluate or measure abdominal core muscle fatigability.

4.1 Validity

Three methods were used to investigate the validity of this test using sEMG properties of the different muscles during the prone bridging test. First, mean relative muscle activity of the different muscles during the test were compared to each other. Second, differences in NMF_{slope} values between muscles were investigated and last, assessment of which muscles limit performance in terms of test endurance time was performed by calculating correlation coefficients between NMF_{slope} values and endurance time, and a multiple stepwise linear regression was executed.

First, the results acquired with regards to the normalized EMG amplitude data support the validity and the claim that abdominal core musculature is more active than back and hip musculature during a prone bridging test. The present study showed a significantly higher activation of the abdominal core musculature during the test (RA = 58.32 % MVIC, EO = 63.56 % MVIC and IO = 61.83 % MVIC) than the back and hip musculature (ILT = 11.7 % MVIC, MF = 13.71 % MVIC, RF = 33.93 % MVIC and BF = 16.82 % MVIC). Abdominal as well as back and hip musculature are all recruited during the test, however, the challenges to the RA, EO an IO were markedly greater than those to the ILT, MF, RF and BF. Lower activity of the IO was expected considering that the more internal muscles, particularly the IO and the transverse abdominis, normally behave in an anticipatory manner, irrespective of loading condition, suggesting a subtle, pro-active control of spinal stability.[20] The IO and transversus abdominis are co-activated during an abdominal hollowing maneuver that requires a deep abdominal contraction.[32] However, these authors suggested that subjects use an abdominal bracing strategy, better known as a global abdominal co-activation, during the prone bridging test. The study of Vera-Garcia et al.[38] showed that the activity of the RA, EO and IO is significantly higher when bracing instead of hollowing. The findings of the present study are in agreement with Schellenberg et al.,[33] who reported very similar mean relative muscle activity during an identical prone bridging test (RA = 52.2 % MVIC, EO = 59 % MVIC, erector spinae = 10.6 % MVIC and hamstrings = 4.3 % MVIC). Tong et al. (2014) also found a clear difference between RA and EO activation (respectively 32.7 % and 31.7 % MVIC) and erector spinae activation (3.3 % MVIC). Though these values are clearly lower than the values found in the present study, this could be explained by the fact that the subjects in the study of Tong et al.[36] only needed to maintain a static prone bridging position for a set period of time (60 s) during their modified version of the prone bridging test.

Second, post hoc one-sample t-testing on all NMF_{slope} data revealed that all slopes differed significantly from zero ($p < 0.05$), signifying fatigue for these muscles. However, pair-wise comparisons between NMF_{slope} values showed significant as well as non-significant differences between the different muscles. The RA had the greatest decline in median frequency and differed significantly from all the other muscles except for the ILT. The BF showed the least rapid decline in median frequency of all the muscles, which differed only significantly from the RA and EO. Clear signs of fatigue were apparent in all abdominal muscles. The back muscles also show fatigue with more fatigability in the ILT than the MF. Fatigue in the hip musculature was significantly lower than in the RA and EO but not-significantly lower for the IO. Lower values of NMF_{slope} of the ILT were expected in this study, especially since lower levels of activation (% of MVIC) during a holding test is associated with a less rapid decline of median frequency.[28] There is no direct explanation for these contradictory results. However, not only fatigability and levels of activation can account for differences in EMG median frequency slopes. Other factors such as fiber-type characteristics, the load the muscles experience and muscle length throughout the test all influence the median frequency characteristics.[27,29]

Finally, correlation coefficients between NMF_{slope} values and endurances times were calculated, and a multiple stepwise linear regression was performed to see which muscles limit performance in terms of endurance time. A moderate to high degree of correlation was found between the endurance time of the prone bridging test and the NMF_{slope} of the RA (r = 0.587), EO (r = 0.410), IO (r = 0.591) and ICLT (r = 0.425). Low correlations were found for the MF (r = 0.196), RF (r = 0.081) and BF (r = -0.046). The results indicated a higher correlation for the ICLT compared to the MF. These correlation coefficients support validity of the prone bridging test for evaluating abdominal muscle fatigue since earlier research have reported similar high correlations between the objective sEMG spectral characteristics of different back muscles and the subjective measurements of recording endurance times in isometric holding tests for measuring back muscle fatigue.[12, 27] Multiple backward linear regression to determine which NMF_{slope} best predicted the endurance time was executed and showed that, of all the abdominal, back and hip muscles, only the NMF_{slope} of the RA could significantly predict the endurance time. The finding that muscle fatigue of the back and hip musculature cannot explain the test endurance time also supports the validity of the prone bridging test. These results are in accordance with the results of Mannion and Dolan,[27] who concluded that the most fatigable muscle best predicted the endurance time during an isometric trunk holding test until failure.

Overall, when interpreting these sEMG measurements, an important clinical conclusion can be made. Although, all abdominal and back muscles clearly fatigued during the test and the NMF_{slope} values of RA, EO, IO and ILT were all significantly correlated with the endurance time, only the RA ultimately seemed to be responsible for limiting performance in terms of endurance time during the prone bridging test. Combined with the highly activated RA, EO and IO during the test, these findings strongly support the validity of the prone bridging endurance test.

Nonetheless, following limitations need to be taken into account. Because bipolar sEMG recordings from several muscles were measured to investigate the EMG power spectra, crosstalk, a signal detected over a muscle but generated by another muscle close to the first one, may have influenced the results in the current study. In this study, the electrode locations of the several muscles were accurately determined, based on anatomical studies, and the guidelines of the

SENIAM project were followed in electrode placement and configuration.[19] The presence of crosstalk is however inherently associated with sEMG recordings. Even if great precautions were taken, as mentioned above, crosstalk cannot be ruled out. Furthermore, Mannion et al.[29] stated that endurance time might be influenced by other factors such as motivation, tolerance of the discomfort of the fatiguing muscles, and especially in a clinical situation, pain or fear of pain. As such, future studies could focus on the influence of these parameters on the performance of the prone bridging test.

4.2 Reliability

The current method for administering the prone bridging test until failure, based on visual inspection and tactile feedback showed excellent intra-tester (ICC = 0.89) as well as excellent inter-tester (ICC = 0.87) reliability. Contrary to the validity of this test, reliability has already been researched. Three studies used a protocol for the prone bridging test similar to the one used in present study. Dennis et al.[15] obtained comparable intra-tester reliability (ICC = 0.89) and inter-tester reliability (ICC = 0.89) results. Schellenberg et al.[33] reported a correlation coefficient of 0.74, signifying a good intra-tester reliability. However, the authors employed a work to rest ratio of 1:4 between the different prone bridging tests, concluding that the second test was partly compromised due to inadequate recovery time. Boyer et al.[8] found an excellent intra-tester reliability (ICC = 0.83) and a good inter-tester reliability (ICC = 0.62) in their study with children aged 8 – 12 years old. Other studies also researched reliability, however, these studies used a modified version of the prone bridging test which makes comparison with current study inappropriate. Tong et al.[36] found an excellent intra-tester reliability (ICC = 0.99) for their sport-specific, dynamic version of the prone bridging test, especially designed for an athletic population. The study of Weir et al.[40] was the only one which showed low intra- and inter-reliability (respectively ICC = 0.21 and ICC = 0.36). Prone bridging in this study however was scored on quality of the test position with a 4-point scale. The poor reliability could be interpreted as a loss of important visual information by observing and evaluating the subjects two-dimensionally and only from one viewpoint in a video-analysis study. The results of these previous comparable studies and the result of present study indicate excellent reliability of the prone bridging test. A plausible explanation for this good reliability might be a superior efficacy of static endurance testing compared to more difficult to administer and evaluate dynamic tests.[35] The prone bridging test is simple to administer as it is initiated with a confirmed starting position and test failure is determined when technique sufficiently deviated from the established norm or when the subject could no longer hold the correct test position. Compared with dynamic endurance testing, there are fewer directions and increased tester objectivity in the ability to define proper and improper technique. It could be argued therefore that fewer subjective determinations need to be made in the prone bridging test, which promotes greater reliability.

In conclusion, to determinate if trunk muscle endurance testing is appropriate from an injury prevention, screening and/or performance perspective, the chosen test needs to be validated as well as provide good reliability. Both factors are important since a measure can be reliable without being valid, however, the reverse is not true.[18] This study strongly supports the validity of the test and the excellent reliability that has been established. The use of this test for these purposes is warranted as such and could provide an important benefit in the field of injury prevention and/or athletic training. Additionally, in order to help interpret the results of the prone bridging test and assist in setting training targets, normative data for both male and female healthy non-athletic as well as athletic subjects have already been established based on an identical prone bridging protocol.[35] With a comparable subject group, comprised of young male and female adults with a diversity in activity level, our results can be placed in the 60th percentile of this normative dataset.

4.3 Perspective

This study is the first to support the validity as well as report the excellent reliability of the prone bridging endurance test until failure, even though this test has already been used extensively in this capacity.[2,16,39,40] These results justify the use of this easy to administer, cost-effective test on a healthy population as a screening tool to detect abdominal core muscle deficiencies and can be used in the fields of injury prevention and athletic training, amongst others. Furthermore, administering this test using the present protocol allows for evaluation and quantification of abdominal core muscle endurance capacity, based on endurance time. Because significant differences in trunk muscle endurance have been demonstrated between healthy subjects and patient populations, the results of this study cannot be extrapolated to these populations. Future studies therefore should research the validity and reliability of this test in specific patient populations.

References

1. Abdelraouf OR, Abdel-aziem AA. The relationship between core endurance and back dysfunction in collegiate male athletes with and without nonspecific low back pain. *Int J Sports Phys Ther.* 2016;11(3):337-344.
2. Ambegaonkar JP, Cortes N, Caswell SV, Ambegaonkar GP, Wyon M. Lower extremity hypermobility, but not core muscle endurance influences balance in female collegiate dancers. *Int J Sports Phys Ther.* 2016;11(2):220-229.
3. Beck TW, Ye X, Wages NP. Local muscle endurance is associated with fatigue-based changes in electromyographic spectral properties, but not with conduction velocity. *J Electromyogr Kinesiol.* 2015;25(3):451-456.
4. Biedermann HJ, Shanks GL, Inglis J. Median frequency estimates of paraspinal muscles: reliability analysis. *Electromyogr Clin Neurophysio.* 1990;30(2):83-88.
5. Biering-Sørensen F. Physical measurements as risk indicators for low back trouble over a one-year period. *Spine (Phila Pa 1976):* 1984;9(2):106-119.
6. Bliss LS, Teeple P. Core stability: the centerpiece of any training program. *Curr Sports Med Rep.* 2005; 4(3):179-183.
7. Boccia G, Rainoldi A. Innervation zones location and optimal electrodes position of obliquus internus and obliquus externus abdominis muscles. *J Electromyogr Kinesiol.* 2014;24(1):25-30.
8. Boyer C, Tremblay M, Saunders T, McFarlane A, Borghese M, Lloyd M, Longmuir P. Feasibility, validity, and reliability of the plank isometric hold as a field-based assessment of torso muscular endurance for children 8-12 years of age. *Pediatr Exerc Sci.* 2013;25(3):407-422.
9. Cicchetti DV, Sparrow SA. Developing criteria for establishing interrater reliability of specific items: applications to assessment of adaptive behavior. *Am J Ment Defic.* 1981;86(2):127-137.
10. Cholewicki J, Panjabi MM, Khachatryan A. Stabilizing function of trunk flexor-extensor muscles around a neutral spine posture. *Spine (Phila Pa 1976).* 1997;22(19):2207-2212.
11. Cohen J. *Statistical power analysis for the behavioral sciences.* 2nd ed. Hillsdale, NJ: Lawrence Earlbaum Associates; 1998.
12. Coorevits P, Danneels L, Cambier D, Ramon H, Vanderstraeten G. Assessment of the validity of the Biering-Sørensen test for measuring back muscle fatigue based on EMG median frequency characteristics of back and hip muscles. *J Electromyogr Kinesiol.* 2008;18(6):997-1005.
13. Cowley PM, Swensen TC. Development and reliability of two core stability field tests. *J Strength Cond Res.* 2008;22(2):619-624.
14. Danneels LA, Coorevits PL, Cools AM, Vanderstraeten GG, Cambier DC, Witvrouw EE, De Cuyper H. Differences in electromyographic activity in the multifidus muscle and the iliocostalis lumborum between healthy subjects and patients with sub-acute and chronic low back pain. *Eur Spine J.* 2002;11(1):13-19
15. Dennis RJ, Finch CF, Elliott BC, Farhart PJ. The reliability of musculoskeletal screening tests used in cricket. *Phys Ther Sport.* 2008;9(1):25-33.
16. Ekstrom RA, Donatelli RA, Carp KC. Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. *J Orthop Sports Phys Ther.* 2007;37(12):754-762.
17. Evans K, Refshauge KM, Adams R. Trunk muscle endurance tests: reliability, and gender differences in athletes. *J Sci Med Sport.* 2007;10(6):447-455.
18. Hayen A, Dennis RJ, Finch CF. Determining the intra- and inter-observer reliability of screening tools used in sports injury research. *J Sci Med Sport.* 2007;10(4):201-210.
19. Hermens HJ, Freriks B, Merletti R, Stegeman D, Blok J, Rau G et al. SENIAM. European recommendations for surface electromyography. Roessingh Research and Development b.v.; 1999.
20. Hodges PW, Richardson CA. Feedforward contraction of transverse abdominis is not influenced by the direction of arm movement. *Exp Brain Res.* 1997;114(2):362–370.
21. Kahraman OB, Sengul Y, Kahraman T, Kalemci O. Developing a reliable core stability assessment battery for patients with non-specific low back pain. *Spine (Phila Pa 1976).* 2016;41(14):844-850.
22. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-198.
23. Konrad P. The ABC of EMG: A practical introduction to kinesiological electromyography. Version 1.4, March 2006.

24. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc*. 2004;36(6):926-934.
25. Lust KT, Sandrey MA, Bulger SM, Wilder N. The effect of 6-week training programs on throwing accuracy, proprioception, and core endurance in baseball. *J Sport Rehabil*. 2009;18(3):407-426.
26. Macintosh JE, Bogduk N. The morphology of the lumbar erector spinae. *Spine (Phila Pa 1976)*. 1987;12(7):658-668.
27. Mannion AF, Dolan P. Electromyographic median frequency changes during isometric contraction of the back extensors to fatigue. *Spine (Phila Pa 1976)*. 1994;19(11):1223-1229.
28. Mannion AF, Dumas, GA, Stevenson JM, Cooper RG. The influence of muscle fibre size and type distribution on electromyographic measures of back muscle fatigability. *Spine (Phila Pa 1976)*. 1998;23:576-584.
29. Mannion AF, O'riordan D, Dvorak J, Masharawi Y. The relationship between psychological factors and performance on the Biering-Sørensen back muscle endurance test. *Spine (Phila Pa 1976)*. 2011;11(9):849-857.
30. McGill SM, Childs A, Liebenson C. Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. *Arch Phys Med Rehabil*. 1999;80(8):941-944.
31. Okada T, Huxel KC, Nesser TW. Relationship between core stability, functional movement, and performance. *J Strength Cond Res*. 2011;25(1):252-261.
32. O'Sullivan PB, Twomey L, Allison GT. Altered abdominal muscle recruitment in patients with chronic back pain following a specific exercise intervention. *J Orthop Sports Phys Ther*. 1998;27(2):114–124.
33. Schellenberg KL, Lang JM, Chan KM, Burnham RS. A clinical tool for office assessment of lumbar spine stabilization endurance; prone and supine bridge maneuvres. *J Am Phys Med Rehabil*. 2007;86(5):380-386.
34. Stevens VK, Bouche KG, Mahieu NN, Cambier DC, Vanderstraeten GG, Danneels LA. Reliability of a functional clinical test battery evaluating postural control, proprioceptioin and trunk muscle activity. *Am J Phys Med Rehabil*. 2006;85(9):727-736.
35. Strand SL, Hjelm J, Shoepe TC, Fajardo MA. Norms for an isometric muscle endurance test. *J Hum Kinet*. 2014;40(1):93-102.
36. Tong TK, Wu S, Nie J. Sport-specific endurance plank test for evaluation of global core muscle function. *Phys Ther Sport*. 2014;15(1):58-63.
37. Thomas JR, Nelson JK, Silverman S (2015). Research methods in physical activity, 7th edition. Champaign, IL: Human Kinetics Publishers. 496 pages.
38. Vera-Garcia FJ, Elvira J LL, Brown S HM and McGill SM. Effects of abdominal stabilization maneuvers on the control of spine motion and stability against sudden trunk perturbations. *J Electromyogr Kinesiol*. 2007;17(5):556-567.
39. Waldhelm A, Li L. Endurance tests are the most reliable core stability related measurements. *J Sport Health Sci*. 2012;1(2):121-128.
40. Weir A., Darby J, Inklaar H, Koes B, Bakker E, Tol JL. Core stability: inter- and intraobserver reliability of 6 clinical tests. *Clin J Sport Med*. 2010;20(1):34-38.
41. Wilkerson GB, Giles J, Seibel D. Prediction of core and lower extremity strains and sprains in collegiate football players: a preliminary study. *J Athl Train*. 2012;47(3):264-272.

PART II

Reliability and validity of trunk flexor and trunk extensor strength measurements using handheld dynamometry in a healthy athletic population

Cedric De Blaiser[1], Roel De Ridder[1] , Tine Willems[1], Lieven Danneels[1], Philip Roosen[1]

[1] *Department of Rehabilitation Sciences, Ghent University, 9000 Ghent, Belgium*

Published in Physical Therapy in Sport, 2018

Full reference:
De Blaiser C, De Ridder R, Willems T, Danneels L, Roosen R. Reliability and validity of trunk flexor and trunk extensor strength measurements using handheld dynamometry in a healthy athletic population. *Phys Ther Sport*. 2018;34:180-186. doi: 10.1016/j.ptsp.2018.10.005.

Abstract

Objectives: To investigate reliability and validity of handheld dynamometry (HHD) strength tests to accurately measure isometric trunk flexion and extension strength.

Methods: Test-retest design and comparative analysis to investigate reliability and validity respectively. Isometric trunk flexion and extension strength, measured with a handheld dynamometer, was compared to isometric strength testing on a stationary isokinetic dynamometer. Different test positions were examined for the HHD measurements for trunk flexion and extension strength.

Trunk muscle strength was calculated in **n**ewton metres (Nm) for both devices. Results of both devices were compared with Pearson correlations and agreement between both methods was explored with Bland-Altman plots. ICC values were calculated to assess HHD intra- and inter-tester reliability.

Results: Reliability was good to excellent for all HHD tests (ICC = 0.67 − 0.93). High correlations were found between the HHD tests and stationary dynamometer tests (r = 0.65 − 0.86). Bland-Altman plots showed agreement between both methods for the trunk flexion test, supported in 30° trunk flexion and for the trunk extension test in a prone position in 0° trunk flexion.

Conclusion: Handheld dynamometry is reliable and a clinically applicable valid method to evaluate maximal isometric trunk flexion strength and maximal isometric trunk extension strength.

Keywords: Core strength; Isometric contraction; Abdominal muscles; Back muscles

1 Introduction

Core strength is considered as a crucial factor for general physical activities and for optimal performance in sports.[6,15,33] Adequate core strength contributes to core stability and allows for optimal production, transfer and control of force and motion throughout the kinetic chain during functional movement.[19,21] Conversely, decreased core muscle functioning can lead to overcompensation of other musculature affecting athletic performance.[31] Inadequate core muscle functioning can also predispose individuals to injuries such as low back pain[35] and increases overall musculoskeletal injury risk.[12,24,27] Therefore, evaluating core strength could be valuable in the context of primary and secondary injury prevention.[28]

Several reliable and validated, easy to use methods are being utilized to assess core musculature characteristics.[26] However, the majority of these tests are endurance based evaluation methods and are not appropriate for determining muscle strength.[9,18,32] To evaluate back muscle endurance for example, the frequently used Biering-Sörensen test has been deemed a valid and reliable test.[9] Similarly, the prone bridging test has proven to be both valid and reliable to establish abdominal muscle endurance capacity.[11] On the other hand, to determine strength of these trunk flexor and extensor muscle groups, no clinical measurement tool is described as both valid and reliable in current literature. To evaluate muscle strength, isokinetic dynamometers, manual muscle testing and handheld dynamometry (HHD) have been described as available methods.[3] Handheld dynamometry provides a quantified measurement of strength and its ease of use, low cost and convenient size may justify a widespread clinical use.[29] Furthermore, it has been described extensively as a valid and reliable measurement method for evaluating upper and lower extremity muscle strength. Although HHD has already been used to measure trunk muscle strength in previous research, there is currently no scientific evidence for HHD as a valid and reliable test to accurately measure maximal isometric trunk flexion and trunk extension strength in a healthy population.[25,34]

Therefore, the main goal of this study is to determine the validity of HHD to measure maximal isometric trunk flexion and trunk extension strength accurately and to examine the intra-tester and inter-tester reliability in a healthy athletic population. Since there is currently no standardized testing position available, validity and reliability were investigated for different test positions. It was hypothesized that the measurements using HHD would show valid force outcomes compared to a commercially available stationary isokinetic dynamometer, which is often used as a reference standard for muscle strength measurements.[1] Furthermore, it was hypothesized that trunk flexion and trunk extension strength measurements by means of HHD would be reliable.

2

2 Methods

2.1 Participants

A convenience sample of thirty healthy subjects voluntarily participated in this study. All participants were required to be over the age of 18, and needed to perform competitive sports activities associated with a professional organization that regularly provides training sessions. The following exclusion criteria were used: A history of traumatic trunk or pelvic injury; a history of acute, sub-acute or chronic low back pain or neurological diseases or disorders; exclusively participating in some form of non-competitive physical activity on a regular basis. All participants refrained from participating in strenuous physical activity for at least one day prior to the test days. The local University Hospital's ethics committee (Ghent University Hospital) approved the study protocol. Participants gave their written informed consent prior to participation.

2.2 Study design & equipment

Validation and reliability procedures for the HHD tests, using a MicroFET 2 handheld dynamometer (Hoggan Scientific LLC, Salt Lake City), were conducted in two phases. In the first phase, validity of the maximal isometric HHD tests was investigated via comparison to maximal isometric contractions on a reliable, commercially available isokinetic dynamometer (BioniX Sim 3 Pro, NiniX Technologies NV, Belgium), which is specifically designed to measure trunk muscle strength. Each participant was required to perform both the isometric BioniX protocol and the isometric HHD protocol in a randomized test order to avoid systematic error. In the second phase, two weeks later, intra-tester and inter-tester reliability of the HHD protocol were investigated. On the first day of reliability testing, each participant performed the same HHD protocol twice, once with each of the two testers. This process was repeated again one week later to prevent learning effects. The tester order was randomized, and it was counterbalanced on the second day of reliability testing. Between two isometric test protocols performed on the same day, in both phases, a resting period of one hour was given to each participant.

2.3 Test protocol

Four different testing positions were adapted from the current literature for the HHD protocol (Figure 1 a-d).[10,23,30] Isometric trunk flexor strength was measured in a supine, straight-knee position and in a supine, straight-knee position with the hips flexed in 30° and the trunk supported in this 30° angle. The dynamometer was placed on the sternum, below the suprasternal notch. Participants were instructed to place their hands on the opposing acromion processes. Isometric trunk extension strength was measured in a prone position and in a prone position

Figure 1 Participant and tester position for the isometric trunk strength testing using handheld dynamometry in (**a**) the supine position, (**b**) the supine position with the trunk supported in 30° flexion, (**c**) the prone position and (**d**) the prone position with the trunk supported in 30° flexion

with the hips flexed in 30° and the trunk supported in this 30° angle. The dynamometer was placed at the height of T4 and the participants were instructed to place the back of their hands on the forehead during the test. Participants were fixated to the table using a strap 10 cm above the lateral malleolus and a strap to prevent pelvic rotation at the height of the ASIS when measuring trunk flexion strength and at the height of the PSIS when measuring trunk extension strength. For all tests, force was applied perpendicular to the trunk. Participants were instructed to gradually build up isometric trunk flexion or trunk extension strength during 2 seconds, followed by a 5-second maximal isometric hold.[5] Prior to contraction, participants were requested to take a normal inhalation and slow expiration during the maximum voluntary contractions. To ensure maximal contraction, one submaximal tryout was performed to familiarize the participants with the testing procedure for each testing position. Furthermore, standardized commands and encouragement were given for each trial. Afterwards, participants were asked if they gave their maximal effort and in case of a non-maximal trial, this repetition was discarded and a re-trial was allowed. Three correctly performed trials were used for data analysis. Fifteen seconds of rest was given between each separate trial. A 5-minute resting period was given between changing of test positions to prevent fatigue from affecting the outcome measures. Termination criteria for all tests were failure to maintain the correct test position, any pain or discomfort experienced, or voluntary discontinuation of the test by the participants. A similar protocol was performed on the BioniX apparatus in an upright position. Fixations on the BioniX were similar to the HHD protocol and the dynamometer was adjusted according to the manufacturer's recommendations.

2.3 Data analysis

Peak torque values from all BioniX trials were measured in newton metres (Nm) and, the mean peak torque value (Nm) over three trials for each test position was calculated. Similarly, peak force values in **n**ewton (N) for the HHD protocol were measured with the handheld dynamometer for each trial and were converted into torque values (Nm) by taking into account the individual moment arm length. The moment arm length was calculated as the distance between the proximal anterior/posterior fixation point (ASIS for the trunk flexion strength tests and PSIS for the trunk extension strength tests) and the center of the HHD. Consequently, peak torque values (Nm) (the mean from three maximum trials for each position of the HHD protocol) were calculated and used for statistical analysis.

2.4 Statistical analysis

Both intra-tester (tester 1, between 2 different days of the reliability testing) and inter-tester reliability (between tester 1 and 2, the same day of reliability testing) of the peak torque values of the HHD protocol were assessed. Intraclass correlation coefficients (ICC) with 95% confidence intervals (CI) were used to assess reliability by utilizing a two-way random effects model with single measure reliability (ICC (2,1)). The interpretation of the ICC was in accordance with Cicchetti and Sparrow[7] with low reliability identified as a value <0.40, moderate reliability 0.40- 0.59, good reliability 0.60- 0.75, and excellent reliability >0.75. SEM values (Nm) were derived by dividing the standard deviation of the mean differences between two measurements by 2 .[13] MDC values were calculated as SEM*1.96*2.

Based on comparison with the stationary dynamometer, the following methods were used to determine the validity of the HHD tests. First, Pearson product-moment correlation coefficients between the two methods were calculated. The interpretation of the correlation coefficients (*r*) was set in accordance with Cohen.[8] Second, Bland-Altman plots with 95% limits of agreement (LoA) (mean difference ± 1.96 SD) were generated to visualize the degree of agreement between the HHD and BioniX measurements and as such ascertain validity.[4] Based on the measured data and the Bland-Altman plots, one sample t-tests were performed to verify whether the mean difference between the HHD tests and BioniX tests differed significantly from zero, which is considered a systematic error or bias. Subsequently, linear regression analysis was performed to investigate proportional bias between the two methods to see whether a positive or negative trend for the differences between the two methods was present throughout the range of measurements. Normality of all the data was verified using the Shapiro-Wilk test. Statistical significance for all tests was accepted at the 5% level.

3 Results

Measurement data from one participant were discarded due to drop out because of an injury between test moments, which was unrelated to the current study. The definitive group consisted of 14 women (21.6 ± 1.4 years, 169.5 ± 4.4 cm, 63.3 ± 5.1 kg) and 15 men (21.9 ± 1.1 years, 180 ± 6.6 cm, 72.2 ± 5.7 kg). Participants were recruited from the following sports: Athletics (9), cycling (5), football (4), dance (4), gymnastics (3), swimming (3) and basketball (1) and performed and average of 5.5 ± 1.7 hours of sport per week. Detailed descriptive statistics of the HHD and BioniX measurements are presented in Table 1.

Table 1 Descriptive statistics of HHD and BioniX measurements and results of one sample t-tests for comparison of the mean difference (BioniX − HHD) between protocols to zero

	N	Mean (Nm)	SD (Nm)	Mean diff (Nm)	SD (Nm)	p-value
BioniX trunk flexion (0°)	29	123.47	±46.97	18.61	±28.8	0.002*
HHD trunk flexion (0°)	29	104.86	±27.4			
BioniX trunk flexion (30°)	29	136.79	±45.8	8.78	±23.85	0.057
HHD trunk flexion (30°)	29	128.01	±41.77			
BioniX trunk extension (0°)	29	195.37	±57.01	0.18	±44.05	0.982
HHD trunk extension (0°)	29	195.19	±43.86			
BioniX trunk extension (30°)	29	218.41	±76.15	-4.79	±52.45	0.627
HHD trunk extension (30°)	29	223.19	±44.63			

N = number of subjects; SD = standard deviation; * = significant difference at the 5% level

Intra-tester and inter-tester reliability values with 95% confidence intervals and accompanying SEM values are presented in Table 2. Excellent intra-tester and inter-tester reliability values were found for all tests (ICC = 0.76 − 0.93) except for the intra-tester reliability of the maximal isometric trunk flexion test starting in 0°, which was good (ICC = 0.67).

As hypothesized, high Pearson product-moment correlations were found between the HHD measurements and the BioniX measurements for the flexion strength tests in 0° ($r = 0.827$) ($p < 0.001$) and the tests in 30° ($r = 0.856$) ($p < 0.001$). For the extension strength tests, a high correlation was found for the tests in 0° ($r = 0.647$) ($p < 0.001$) as well as for the tests in 30° ($r = 0.741$) ($p < 0.001$).

Table 2 Intra-tester and inter-tester reliability of the HHD tests for trunk flexor and extensor strength and corresponding SEM values (Nm)

	N	ICC (2,1)	95% CI for ICC	SEM (Nm)	MDC (Nm)
Intra-tester Trunk flexion (0°)	29	0.67	0.4 − 0.83	26.41	73.2
Intra-tester Trunk flexion (30°)	29	0.9	0.8 − 0.95	17.69	49.03
Intra-tester Trunk extension (0°)	29	0.93	0.92 − 0.98	14.42	39.97
Intra-tester Trunk extension (30°)	29	0.8	0.16 − 0.93	33.02	91.53
Inter-tester Trunk flexion (0°)	29	0.78	0.28 − 0.91	17.98	49.83
Inter-tester Trunk flexion (30°)	29	0.93	0.82 − 0.97	16.45	45.6
Inter-tester Trunk Extension (0°)	29	0.76	0.56 − 0.88	20.88	57.88
Inter-tester Trunk extension (30°)	29	0.82	0.17 − 0.94	31.53	87.4

N = number of subjects; CI = confidence interval; SEM = standard error of measurement (Nm); MDC = minimal detectable change

Bland-Altman plots are presented in Figure 2 (a & b). Regarding the trunk flexion strength tests starting in 0°, the one sample t-test concludes that the mean of differences between BioniX and HHD measurements differs significantly from zero ($p = 0.002$), as shown in the Bland-Altman plot. This systematic difference of 18.61 Nm indicates significantly higher BioniX measurements compared to the HHD measurements in this position. Furthermore, linear regression of the differences

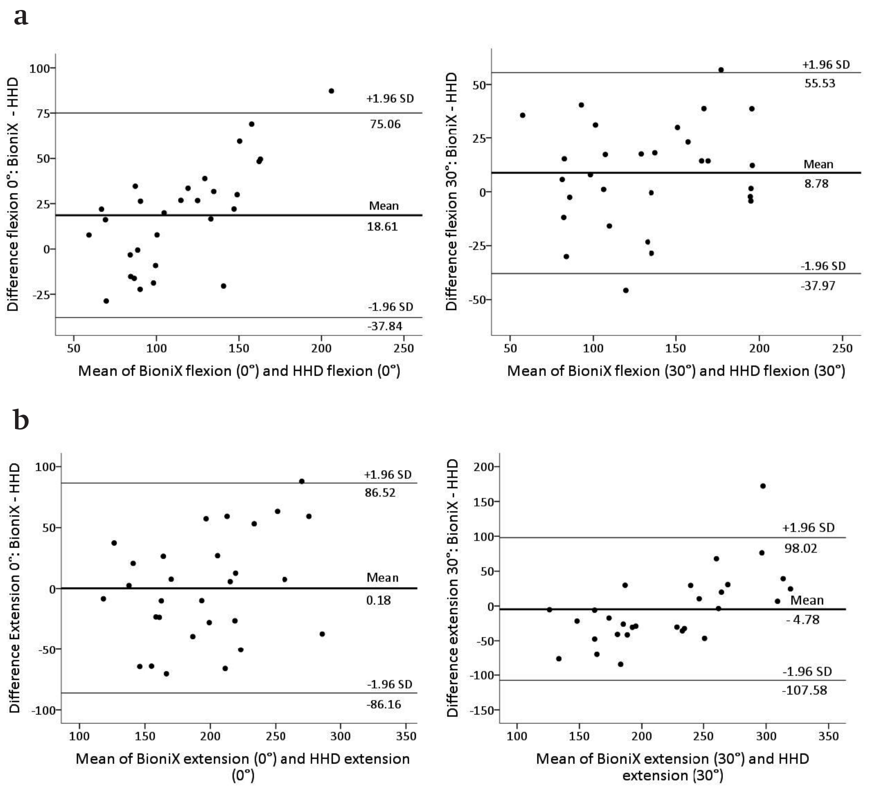


Figure 2 Bland-Altman plots for (**a**) the trunk flexion strength tests in 0° and 30° and (**b**) the trunk extension strength tests in 0° and 30°. Mean difference between the both methods and 95% limits of agreement are visualized with horizontal lines

between the methods on the average of the methods shows a slope (B = 0.57) significantly different from zero (p < 0.001). This implies proportional bias for this position and indicates that the difference between the methods unequally varies throughout the range of measurements. For these tests, the 95% limits of agreement ranged between -37.84 Nm and 75.06 Nm. The Bland-Altman plot for the flexion strength tests in 30° flexion also shows higher values for the BioniX measurements compared to the HHD measurements, however, this difference (8.78 Nm) was not significantly different from zero (p = 0.057). Visual inspection and linear regression could not point out proportional bias with a regression slope not significantly differing from zero (p = 0.363). The 95% limits of agreement varied between -37.97 Nm and 55.53 Nm. For the trunk extension tests in 0° the mean difference (0.18

Nm) between both methods was not significantly different from zero (p = 0.982), as shown in the Bland-Altman plot. The regression slope was not significantly different from zero (p = 0.082), indicating the absence of proportional bias and the 95% limits of agreement varied between -86.16 Nm and 86.52 Nm. Lastly, the Bland-Altman plot for the extension strength tests in 30° also shows a mean difference (-4.78 Nm) which was not significantly different from zero (p = 0.627). However, regression analysis did show proportional bias between the two methods with a regression slope (B = 0.59) significantly differing from zero (p < 0.001), indicating a non-uniform variability of the paired differences along the range of measurements. The 95% limits of agreement for these tests varied between -107.58 Nm and 98.02 Nm.

4 DISCUSSION

The main goal of this study was to investigate whether handheld dynamometry to measure isometric trunk flexion and trunk extension core strength is a reliable and valid method. Good to excellent reliability was found for all HHD tests and a high correlation was found between these tests and the reference method. Furthermore, the trunk flexion HHD test supported in 30° and the trunk extension HHD test in 0° showed agreement compared to the reference method for measuring trunk strength. Based on current results, the tests in these two positions are considered as reliable and valid tests and these positions are considered to be appropriate to measure isometric trunk muscle strength with the use of a HHD.

Many different positions to measure trunk muscle performance are described in current literature and no standardized protocol for HHD trunk strength testing was available to adapt for this study. Therefore, the positions and testing protocols for the current study were based on recent literature describing maximal voluntary isometric contraction (MVIC) testing for trunk musculature.[10,23,30] The clinical feasibility and the possibility for optimal test standardization in these positions, with regards to patient fixation and examiner positioning, were taken into account when choosing the appropriate test positions. Besides the trunk flexion strength test in a neutral position, a sit-up style position for trunk flexion strength testing was used based on the study protocols of Danneels et al.[10]. and Stevens et al.[30], with the trunk supported in a 30° trunk flexion, as suggested by Konrad.[23] Moreover, the use of a straight-knee position enables a high abdominal trunk flexor synergy, compared to a bent-knee position.[2] Similar to the flexion strength protocol, isometric trunk extension strength was evaluated in the neutral prone position, as well as in a supported 30° trunk flexion position.[27,23,30]

A test-retest study design was implemented to investigate intra-tester and inter-tester reliability for measuring maximal trunk muscle strength using the

HHD. The current standardized protocol showed overall excellent intra- and inter-tester reliability, except for the intra-tester reliability for the trunk flexion test in 0°, which was good. These results for HHD are comparable with the manufacturer established excellent test-retest reliability of the BioniX apparatus for isometric trunk flexion and extension strength tests in different positions (ICC (3,1) = 0.95 – 0.99). Furthermore, these results are in accordance with a systematic review on HHD reliability for measuring maximal muscle strength in general (Stark et al., 2011).[29] These authors concluded that a HHD is a reliable instrument for muscle strength assessment in a clinical setting, provided the same participant position and the same standardized test method is used for every test. However, Moreland et al.[25] observed poor inter-rater reliability for isometric trunk strength tests, measured with HHD, for flexion strength (ICC = 0.25) as well as extension strength (ICC = 0.24) tests. As test standardization is considered crucial for good reliability, variability could have been high in this study as no straps were used for participant fixation, prohibiting optimal force production. Additionally, they used a modified Biering-Sörensen position to measure trunk extension strength, failing to provide a support surface for the trunk during isometric testing.

To examine validity, the agreement between the isometric HHD protocol and the stationary dynamometer protocol was examined. A first step towards validation was to investigate the correlation between the HHD tests and BioniX tests. High correlations were found between the measurements of each HHD test and the corresponding BioniX test, indicating a strong relationship between both methods for measuring isometric trunk muscle strength. However, since both these methods supposedly measure strength in a similar condition, a high correlation coefficient can be expected, independently from the amount of agreement between both methods. Therefore, Bland-Altman plots were generated, since it is a method often used to determine validity of a new measurement method based on agreement with a reference method.[4]

Although the plot for the trunk flexion test in 30° showed a non-significant systematic error, an equal scatter around the line of equality with no obvious trends of the data points was seen, which suggests an equal difference between the two methods throughout the range of strength measurements. This is a prerequisite for agreement between two methods.[16] Furthermore, a relative small range of 95% limits of agreement was present, compared to the method in 0°. On the other hand, the plot for the trunk flexion test in 0° showed a significant systematic error, suggesting overall lower HHD strength measurements compared to the BioniX reference measurements. More important, the plot did not display an equal scatter of data points around the line of equality. Rather, a positive linear association was seen between the average measurements and differences between the measurements. This implies proportional bias and both methods in the 0° position do not agree equally throughout the range of measurements, contrary to the test position in 30°. This results from unequal differences between the test methods through the range of measurements. These variable differences between methods might be the result of inefficient force generation of the abdominal muscles for the HHD measurements in the supine position in 0°. Indeed, an increased external moment of the gravitational force acting on the trunk, as a result of a supine position, creates a mechanical disadvantage for generating force.[2] Furthermore, Keller and Roy[20] concluded that, based on the length-tension relationship of the abdominal muscles, the posture for optimal muscle strength is a 20° to 30° trunk flexion position. These factors could lead to a possible inefficient abdominal force generation in a supine position. This hypothesis is corroborated with the fact that in general the HHD measurements are significantly lower than the BioniX measurements in this position. The ineffecient force generation could cause meaningful variability between both methods and, combined with the systematic error, results in disagreement between both methods in the 0° position. In conclusion, there is an overall agreement between both methods in the 30° position but not in the 0° position, reinforcing the validity for the supine trunk flexion strength test in 30°.

For the trunk extension strength test in 0° there was no significant difference between the HHD method and BioniX method on average, no proportional bias could be discerned and, compared to the method in 30°, a relative small 95% limits of agreement was present. The trunk extension strength test in 30°, however, did not display agreement with the BioniX test. Although there was no significant absolute bias between the two methods, a linear relation was seen between the difference of the methods and the average, signifying proportional bias as a result of unequal differences between the methods through the range of measurements. It can be hypothesized that maintaining isometric resistance in this position is difficult for the rater in high strength participants due to additional hip extensor muscle activity. Indeed, Kocjan and Sarabon[22] concluded that performing isometric trunk extension with hip flexion leads to higher force output compared to a neutral position as a result of an optimal length-tension position for the hip extension muscles. In conclusion, an agreement was obtained between the two methods in the 0° position but not in the 30° position, reinforcing the validity for the prone trunk extension strength test in 0°.

The following considerations need to be taken into account when interpreting the results. Although the HHD protocol and the BioniX protocol were adapted to one another as well as possible, they did differ in terms of testing positions since the HHD tests in a supine or prone position were compared to the validated upright position in the BioniX.[17] However, the main goal of our study was to investigate whether a novel, clinically feasible HHD method for measuring isometric trunk flexion and extension strength in a supine or prone position could produce similar strength measurements compared to a reliable reference method for measuring trunk strength, which is generally performed on a stationary dynamometer in an upright position, in order to investigate agreement between both methods and consequently validity of the novel HHD method.

Second, the arrangement of the 95% limits of agreement is used for visual interpretation of the agreement between two methods. A smaller range implies better agreement, however, considering whether two methods have a high degree of agreement depends on the clinical context.[16] Since there are no studies available comparing results of HHD and stationary dynamometry for trunk strength measurements and normative data for HHD trunk strength measurements are not available, a clear interpretation of the range of 95% limits of agreement within this study is challenging. Therefore, while agreement between the HHD and the stationary dynamometer was established and, HHD is considered a valid method for measuring isometric trunk strength, it is not advised to use both methods interchangeably when performing assessment of isometric trunk flexion or extension strength within a group or when performing assessment and re-assessment of trunk strength within the same subject. Furthermore, based on the MDC values, a HHD might not be the most sensitive instrument for monitoring true changes in isometric trunk flexion and trunk extension strength although these measurements were proven to be reliable.

5 Conclusion

Based on the results of this study, the isometric trunk flexion test with the trunk supported in 30° flexion and the isometric trunk extension test in 0° are reliable HHD tests which are in agreement with the reference BioniX measurements. As such, they are considered a valid and reliable alternative to specifically measure trunk muscle strength in a clinical practice setting and are easy to use, portable and cost-effective in comparison with the BioniX reference method. The use of these tests is warranted as such and could provide an important benefit in screening for injury prevention and rehabilitation in athletes.

References

1. Alfuth M, Hahm MM. Reliability, comparability, and validity of foot inversion and eversion strength measurements using a hand-held dynamometer. *Int J Sports Phys Ther.* 2016;11(1):72-84.
2. Andersson EA, Nilsson J, Ma Z et al. Abdominal and hip flexor muscle activation during various training exercises. *Eur J Appl Physiol Occup Physiol.* 1997;75(2):115-123.
3. Arnold CM, Warkentin KD, Chilibeck PD et al. The reliability and validity of handheld dynamometry for the measurement of lower-extremity muscle strength in older adults. *J Strength Cond Res.* 2010;24(3): 815-824.
4. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet.* 1986;1(8476):307-310.
5. Bohannon RW. Reference values for extremity muscle strength obtained by hand-held dynamometry from adults aged 20 to 79 years. *Arch Phys Med Rehabil.* 1997;78(1):26-32.
6. Butcher SJ, Craven BR, Chilibeck PD, Spink KS, Grona SL, Sprigings EJ. The effect of trunk stability training on vertical takeoff velocity. *J Orthop Sport Phys Ther.* 2007;37(5):223-231.
7. Cicchetti DV, Sparrow SA. Developing criteria for establishing interrater reliability of specific items: applications to assessment of adaptive behavior. *Am J Ment Defic.* 1981 86(2):127-137.
8. Cohen J. *Statistical power analysis for the behavioral sciences.* 2nd ed. Hillsdale, NJ: Lawrence Earlbaum Associates; 1998.
9. Coorevits P, Danneels L, Cambier D et al. Assessment of the validity of the Biering-Sørensen test for measuring back muscle fatigue based on EMG median frequency characteristics of back and hip muscles. *J Electromyogr Kinesiol.* 2008;18(6):997-1005.
10. Danneels LA, Vanderstraeten GG, Cambier DC et al. A functional subdivision of hip, abdominal, and back muscles during asymmetric lifting. *Spine (Phila PA 1976).* 2001;26(6):E114-121.
11. De Blaiser C, De Ridder R, Willems T et al. Evaluating abdominal core muscle fatigue: Assessment of the validity and reliability of the prone bridging test. *Scand J Med Sci Sports.* 2018;28(2):391-399.
12. De Blaiser C, Roosen P, Willems T, Danneels L, Bossche L Vanden, De Ridder R. Is core stability a risk factor for lower extremity injuries in an athletic population? A systematic review. *Phys Ther Sport.* 2018;30:48-56.
13. de Vet HC, Terwee CB, Knol DL et al. When to use agreement versus reliability measures. *J Clin Epidemiol.* 2006;59(10):1033-1039.
14. Dolny DG, Collins MG, Wilson T et al. Validity of lower extremity strength and power utilizing a new closed chain dynamometer. *Med Sci Sports Exerc.* 2001;33(1):171-175.
15. Faries MD, Greenwood M. Core training: stabilizing the confusion. *Strenght Cond J.* 2007;29(2):10-25.
16. Giavarina D. Understanding Bland Altman Analyis. *Biochem Med (Zagreb).* 2015;25(2)141-151.
17. Guilhem G, Giroux C, Couturier A et al. Validity of trunk extensor and flexor torque measurements using isokinetic dynamometry. *J Electromyogr Kinesiol.* 2014;24(6):986-993.
18. Hall GL, Hetzler RK, Perrin D et al. Relationship of timed sit-up tests to isokinetic abdominal strength. *Res Quart Exerc Sport.* 1992;63(1):80-84.
19. Ireland ML, Willson JD, Ballantine BT et al. Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther.* 2003;33(11):671-676.
20. Keller TS, Roy AL. Posture-dependent isometric trunk extension and flexion strength in normal male and female subjects. *J Spinal Disord Tech.* 2002;15(4):312-318.
21. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-189.
22. Kocjan A, Sarabon N. Assessment of isometric trunk strength – The relevance of body position and relationship between planes of movement. *J Sports Sci Med.* 2014;13(2):365-370.
23. Konrad P. *The ABC of EMG: A practical introduction to kinesiological electromyography.* Version 1.4. Noraxon USA, Inc.: Scottsdale, Arizona (USA); March 2006.
24. Leetun DT, Ireland ML, Willson JD et al. Core stability measures as risk factors for lower extremity injury in ahtletes. *Med Sci Sports Exerc.* 2004;36(9):926-934.
25. Moreland J, Finch E, Stratford P et al. Interrater reliability of six tests of trunk muscle function and endurance. *J Orthop Sports Phys Ther.* 1997;26(4):200-208.

26. O'Connor S, McCaffrey N, Whyte E, Moran K. The development and reliability of a simple field based screening tool to assess core stability in athletes. *Phys Ther Sport.* 2016;20:40-44.
27. Raschner C, Platzner H, Patterson C et al. The relationship between ACL injuries and physical fitness in young competitive ski racers: a 10-year longitudinal study. *Br J Sports Med.* 2012;46(15):4065-1071.
28. Santos TR, Andrade JA, Silva BL, Garcia AF, Persichini Filho JG, Ocarino Jde M, Silva PL. Active control stabilization of pelvic position in the transverse plane: an evaluation of soccer players' performance. *Phys Ther Sport.* 2014;15(3),189-193.
29. Stark T, Walker B, Phillips JK et al. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: A systematic review. *PM R.* 2011;3(5):472-479.
30. Stevens VK, Bouche KG, Mahieu NN, et al. Reliability of a functional clinical test battery evaluating postural control, proprioception and trunk muscle activity. *Am J Phys Med Rehabil.* 2006;85(9):727-736.
31. Tanaka NI, Komuro T, Tsunoda N et al. Trunk muscularity in throwers. *Int J Sports Med.* 2013;34(1):56-61.
32. Tong TK, Wu S, Nie J. Sport-specific endurance plank test for evaluation of global core muscle function. *Phys Ther Sport.* 2014;15(1):58-63.
33. Willardson JM. Core stability training: applications to sports conditioning programs. *J Strength Cond Res.* 2007;21(3):979-985.
34. Willson JD, Davis IS. Lower extremity strength and mechanics during jumping in women with patellofemoral pain. *J Sport Rehabil.* 2009;18(1):76-90.
35. Willson JD, Dougherty CP, Ireland ML et al. Core stability and its relationship to lower extremity function and injury. *J Am Acad Orthop Surg.* 2005;13(5):316-325.

PART III

Reliability of two functional clinical tests to evaluate trunk and lumbopelvic neuromuscular control and proprioception in a healthy population

Cedric De Blaiser[1], Roel De Ridder[1], Tine Willems[1], Lieven Danneels[1], Philip Roosen[1]

[1] *Department of Rehabilitation Sciences, Ghent University, 9000 Ghent, Belgium*

Accepted for publication in Brazilian Journal of Physical Therapy, 2018

Full reference:
De Blaiser C, De Ridder R, Willems T, Danneels L, Roosen R. Reliability of two functional clinical tests to evaluate trunk and lumbopelvic neuromuscular control and proprioception in a healthy population [published online ahead of print November 10, 2018]. *Br J Phys Ther.* doi:10.1016/j.bjpt.2018.10.014.

Abstract

Objectives: The need to accurately assess trunk and lumbopelvic proprioception and neuromuscular control is widely accepted. However, based on current literature, there is a lack of reliable clinical tests to evaluate these aspects in clinical practice. The objective of this study is to investigate intra-tester and inter-tester reliability of the lateral step down test and the lumbopelvic position-reposition test in a healthy population.

Methods: Protocol and scoring methods were developed for the lateral step down test and lumbopelvic position-reposition test, used to assess trunk and lumbopelvic neuromuscular control and proprioception respectively. Each test was performed once by thirty healthy participants and video analysis for test scoring was performed. Three items on the lateral step down test were scored to evaluate neuromuscular control and, four items on the lumbopelvic position-reposition test were scored to evaluate proprioception. Aggregate scores for each test were calculated based on the separate item scores. Intraclass correlation coefficients and linear weighted Kappa coefficients were determined for intra- and inter-tester reliability.

Results: Based on the aggregate score, excellent intra- and inter-tester reliability (ICC(2,1) = 0.73–0.88) was found for both tests. Moderate/almost perfect intra-and inter-tester agreement (K = 0.62–0.91) was found for the separate items of the lateral step down test and fair/substantial agreement (K = 0.25 – 0.76) for the items of the lumbopelvic position-reposition test.

Conclusion: Current testing protocol and scoring method for the lateral step down test is reliable. Adjustments for the scoring method of the lumbopelvic position-reposition test is warranted to improve reliability.

Keywords: Reliability; Proprioception; Injury prevention; Screening; Lumbopelvic hip complex; Core stability

1 Introduction

Assessment of core stability has gained widespread attention over the last decade since it is associated with low back pain, musculoskeletal injury risk, and athletic function.[11,14,15,18,28] Core stability is defined as dynamic trunk and lumbopelvic control that allows for production and regulation of force, which is transferred throughout the kinetic chain during movement.[11] Core stability requires the integration of core muscle strength, endurance, neuromuscular control and proprioception.[14,21,30] Neuromuscular control is the ability to produce efficient movement during task performance as a result of precisely coordinated muscular activity at the right time, for the correct duration and with the right combination of forces.[4] Proprioception is the ability to sense joint position and movement based on afferent sensory input from joints, tendons, and associated deep tissue proprioceptors.[8]

Inadequate core neuromuscular control and proprioception have been proven to be risk factors for lower extremity injuries since they compromise dynamic joint stability and lead to altered movement patterns.[26,30] In general, neuromuscular control is assessed by evaluating motion quality and control during a specific movement whereas proprioception of a segment can be assessed with motion detection threshold testing or through evaluating the ability to position and reposition the segment in a specific posture.[8,29] These aspects are often evaluated in lab situations with expensive or not commercially available equipment and have a limited use in clinical practice compared to clinical screening tests.

The lateral step down test[2,19,20] and the lumbar position-reposition test[23] are suggested as feasible clinical tests to evaluate trunk and lumbopelvic neuromuscular control and proprioception respectively and, they require a minimal amount of equipment to perform. Adequate reliability of such clinical screening tests is relevant since it is a prerequisite for test validity.[6,7,24] Although evaluation of reliability of these tests has been performed in current literature, there is contradictory evidence for reliability of the lateral step down test and, reliability of the lumbar position-reposition test was based on a scoring method using laboratory equipment.[2,19,20,23]

In conclusion, reliable tests with feasible scoring methods to measure trunk and lumbopelvic neuromuscular control and proprioception are lacking. The available protocols for the lateral step down test and the lumbar position-reposition test were adapted into novel test protocols and scoring methods and, scoring criteria and video based test assessment were developed. The aim of this study is to investigate the intra- and inter-tester reliability of the novel lateral step down test and lumbopelvic position-reposition test, which evaluate trunk and lumbopelvic neuromuscular control and proprioception respectively, by comparing video based test scores in a healthy population.

2 Methods

2.1 Participants

Sixty healthy participants over the age of 18, enrolled in teacher training studies at the Artevelde University College and the University College Ghent, voluntarily participated and were randomly assigned to perform one of both tests. Thirty participants (17♂, 13♀; age: 19.38 ± 1.04 years; BMI (body mass index): 22.34 ± 2.25 kg/m^2) were selected for the lateral step down test and thirty participants (15♂, 15♀; age: 19.5 ± 1.5 years; BMI: 21.44 ± 1.94 kg/m^2) were selected for the lumbopelvic position-reposition test. The following exclusion criteria were used: A history of traumatic pelvic and/or trunk injury; a history of acute, sub-acute or chronic low back pain or neurological diseases or disorders.

2.2 Study design

Tests were performed in a controlled clinical setting and, video based test scoring was independently performed after test completion by two examiners. The same examiner provided test instructions and supervised all test performances. Intra-tester reliability was investigated by comparing two test scores of the same examiner (given two weeks apart to prevent recall bias). Inter-tester reliability was investigated by comparing test scores given independently by 2 different examiners. The examiners are experienced physical therapists (6 and 13 years) and were trained to standardize test scoring. One training session was held to familiarize the examiners with the scoring protocols. Afterwards, both examiners scored 15 test subjects for each test and a consensus meeting was held to compare scores and fine-tune scoring methods. The local commission for Medical Ethics (UZ Ghent) approved the study and participants gave their written informed consent prior to participation.

2.3 Test protocol and scoring method development

Development of the test protocols and scoring methods involved a combination of judgment and expert consensus opinion methodology.

An extensive literature search was performed on the topic of neuromuscular control, proprioception and the possible assessment methods. Investigator agreement was reached on a dynamic movement control test and an active position-reposition test as appropriate clinical assessment tools to measure trunk and lumbopelvic neuromuscular control and proprioception respectively. Existing tests were used as basis for protocol development and were adapted with regards to standardization.

Items for scoring, item scoring descriptions and scoring methods were determined for each test and a consensus opinion method was used in which a panel of expert clinicians (n = 3; between 13 and 25 years of experience in motor control, low back pain and musculoskeletal rehabilitation) was involved in testing and commenting on the appropriateness of the items, their descriptions and the scoring methods.

2.4 Test protocols

Lateral step down test protocol

The current protocol was based on existing tests.[2,19,20] Participants stood on the edge of a 30 cm high box (25 cm for people shorter than 170 cm) in unipodal stance (foot pointed forward) and were asked to perform a series of lateral step downs, which were executed at a self-chosen, comfortable speed with the contralateral knee extended and contralateral hip slightly flexed. The correct test performance was demonstrated by the same examiner while the following instructions were given for standardization: "Cross arms at the chest and don't use them to keep balance. Keep looking forward. Bend the knee and lower the free leg towards the ground in a controlled manner. Keep the trunk upright. Keep the pelvis horizontal. Keep the knee of the stance leg on a line which connects the hip with the second toe of the stance leg. When the opposite heel touches the ground, do not transfer weight and return to the initial position. Repeat this sequence 5 times."

Two practice trials were allowed to provide feedback in case of a faulty test performance, followed by the actual execution of five consecutive lateral step downs. Trials were repeated if the subject failed to touch the ground with the contralateral heel or stepped off the box. For this study, only one leg was tested in a randomized order.

Lumbopelvic position-reposition test protocol

The protocol was based on the study of Stevens et al.[23] Proprioception was evaluated by determining the repositioning accuracy of the trunk and lumbopelvic regions into a reference position, after having actively moved from full spinal flexion to extension during sitting. The participant was seated with 85 degrees of knee flexion, feet placed at hip width and arms hanging freely alongside the trunk. The participant was placed in a neutral spine reference position. The neutral position was halfway between full extension and a flat position of the spine.[5] The participant was then asked to perform three movements between spinal flexion and extension at a self-chosen, comfortable speed. After performing these movements, the participant was asked to accurately reassume the reference position.

2.5 Test scoring

Tests were filmed using a video camera (Canon Legria hfG10, Canon Inc., Tokyo, Japan; 25 frames/second; effective resolution: 1.56 pixels). For both tests, the camera was placed at a distance of 3 m and a height of 50 cm. The camera was placed in line with the stance leg for the lateral step down test and filmed the test in the frontal plane. It was placed in line with the lumbar spine for the lumbopelvic position-reposition test and filmed the test in the sagittal plane.

Lateral step down test scoring

Movement patterns of the trunk, pelvis and lower extremity during the step down were evaluated in three items: dynamic balance (1), knee valgus/hip internal rotation (HIR) (2) and pelvic control (3). A score of 0, 1, 2 or 3 could be attributed to each item. Item scores were combined into an aggregate score with a minimum of 0 and a maximum of 9 points with 9 the best possible score. An open source video editing program for analyzing kinematics (Kinovea, Version 0.8.15) was used for test scoring. This program enabled the examiners to indicate reference points, draw lines between body segments and calculate angles in order to quantify movement pattern deviations. In general, examiners were instructed to score the items with as few as possible video playback repetitions, however, repeated viewing was allowed when in doubt. An overview of the scoring method is given in Appendix Table 1.

For 'dynamic balance', movements of the trunk and free leg were evaluated during step downs. 'Dynamic balance' was evaluated in general for the 5 consecutive trials with normal video playback speed. Perfect balance (no movement of the trunk or free leg for 5 repetitions) received a score of 3. Small movement of trunk or free leg in 2 or more repetitions received score 2. Score 1 corresponded with moderate movement of trunk or free leg in 2 or more repetitions. Score 0 was given in case of large movement of the trunk or free leg in 2 or more repetitions or when the hands were not held on the shoulders during the execution of the test. In case of doubt between two scores the lower score was given.

Scoring the items 'knee valgus/HIR' and 'pelvic control' was performed on one and the same of the 5 step downs. It is the objective of the scoring for these items to assess the best representative of the 5 repetitions. The examiner viewed 5 consecutive repetitions and was instructed to choose the best one for scoring if 5 similar repetitions were observed. However, if variability between the different repetitions was seen, the best and the worst quality repetitions were left out and the best repetition of the remaining repetition was chosen as the best representative. A good performance on the lateral step down test was in accordance with the standardized instructions given to the subject as described above.

For the item 'knee valgus/HIR', the video was slowed down to half speed with Kinovea and paused at the moment of heel-contact of the contralateral leg for the chosen repetition. The amount of knee valgus was measured to evaluate medial knee collapse and consequently the amount of functional hip internal rotation.[9] Therefore, a line was drawn from the hip towards the second metatarsal (Figure 1). If this line passed through the centre of the patella , the participant scored 3 or 2. Differentiation between a score 2 and 3 was based on normal speed video playback:

Figure 1 Screenshot with reference lines and angle calculation for the items ‘knee valgus/HIR’ and ‘pelvic control’ of the lateral step down test

score 2 if the knee made small oscillating movements around the neutral line during the step down; score 3 if a perfect steady step down was performed with no oscillating movements. If the centre patella was not in line with the second metatarsal and the hip joint at the moment of heel-contact, the participant scored 1 or 0: score 1 if the middle of the patella was above or lateral of the hallux (evaluated with a vertical line drawn upwards from the hallux); score 0 if the centre patella was medial of the hallux.

‘Pelvic control’ was assessed by evaluating the height difference of the left and right ASIS in Kinovea. The video was slowed down to half speed with Kinovea and paused at the moment of heel-contact. The left and right ASIS were connected with a line and the angle with the horizontal plane was calculated (Figure 1). Score 3 was given when the line connecting both ASIS was horizontal. An angle between 0° and ≤ 10° received score 2. An angle between 10° and ≤ 20° resulted in score 1. Score 0 was given with an angle > 20° or in case of explicit weight transfer on the contralateral leg.

Lumbopelvic position-reposition test scoring

A scoring method was developed based on repositioning of the trunk and lumbopelvic regions. The recording of this test was viewed once and a screenshot of the neutral reference position and a screenshot of the repositioning into the reference position after three movement cycles were compared. Four items were evaluated: position of the pelvis (1), lumbar spine curvature (2), thoracic spine curvature (3) and inclination of the thorax (4). Item scores were combined into an aggregate score ranging from 0 to 10, with 10 being the best score. Possible scoring options for the first two items were: score 3: repositioning = original position (perfect repositioning, no differences between the two screenshots for this region); score 2: small deviation (near perfect repositioning, small difference discernible between the two screenshots for this region); score 1: large deviation (undeniable difference between the two screenshot for this region); score 0: impossibility to reposition (repositioning is impossible due to obvious coordination dysfunction). Possible scoring options for item 3 and 4 were: score 2: repositioning = original position (perfect repositioning, no differences between the two screenshots for this region); score *1*: small deviation (near perfect repositioning, small difference discernible between the two screenshots for this region); score 0: large deviation (undeniable difference between the two screenshot for this region). An overview of the scoring method is presented in Appendix Table 1.

2.6 Statistical analyses

Intra- and inter-tester reliability, based on the aggregate scores of the lateral step down test and the lumbopelvic position-reposition test were calculated. Intraclass correlation coefficients (ICC) with 95% confidence intervals (CI) were calculated with a two-way random effects model with single measure reliability (ICC (2,1)). Interpretation of the ICC values was in accordance with Cicchetti and Sparrow.[3] Standard error of measurement (SEM) was calculated (SEM=SD 1−ICC). Minimal detectable changes (MDC), based on the 95% confidence intervals, were calculated with 1.96 x √2 x SEM.

Intra- and inter-tester reliability of the ordinal scores on the separate test items of both tests was investigated with linear weighted kappa coefficients and the corresponding percentage agreement. Interpretation of the kappa coefficients was in accordance with Landis and Koch.[13] For each separate item, the percentage agreement between two given scores was calculated. Sample size requirements to achieve a significance level of 0.05 with a power of 0.8 were calculated based on the study of Walter et al.[27] Statistical analyses were conducted with the statistical software package SPSS (v25.0).

3 Results

Descriptive statistics for both tests are presented in Table 2. ICC values with 95% confidence intervals and accompanying SEM and MDC values are presented in Appendix Table 3. Good to excellent intra- and inter-tester reliability values were found for the aggregate scores for both tests.

Table 2 Descriptive statistics of the lateral step down test and lumbopelvic position-reposition test

	N	Mean	SD	Min - Max
Lateral step down test (Examiner 1)	30	4.5/9	±1.2	1/9 – 7/9
Lateral step down test (Examiner 2)	30	4.4/9	±1.4	0/9 – 8/9
Lumbopelvic position-reposition test (Examiner 1)	30	6.9/10	±1.8	2/10 – 10/10
Lumbopelvic position-reposition test (Examiner 2)	30	7.3/10	±1.4	5/10 – 10/10

N = number of subjects; SD = standard deviation

Kappa coefficients with 95% confidence intervals and accompanying percentage agreement are presented in Appendix Table 4. Intra-tester agreement for the items 'dynamic balance' and 'knee valgus/HIR' of the lateral step down test revealed almost perfect agreement and, substantial intra-tester agreement was found for the item 'pelvic control'. Inter-tester agreement for all three items of the lateral step down test was substantial.

Intra-tester agreement for the lumbopelvic position-reposition test was substantial for the items 'position of the pelvis', 'lumbar spine curvature' and 'inclination of the thorax' and moderate for the item 'thoracic spine curvature'. Inter-tester agreement for the item 'position of the pelvis' and 'lumbar spine curvature' was substantial. Inter-tester agreement for the items 'thoracic spine curvature' and 'inclination of the thorax' was fair.

4 Discussion

Based on the ICC value (with 95% CI) of the aggregate scores on the lateral step down test, good to excellent intra- and inter-tester reliability can be expected. The separate items showed substantial to almost perfect intra- and inter-tester agreement. The lowest kappa coefficient was shown for the intra-tester agreement of the item ‘pelvic control’, but was nonetheless above 0.61, which is used as clinically acceptable agreement.[1,10,12,16,22] Based on the expected good to excellent reliability of the aggregate scores, and the substantial to perfect agreement on the separate items, the authors of this study consider the current scoring method of the lateral step down test reliable for use in clinical practice with healthy participants. However, caution is needed for the item ‘pelvic control’. The 95% CI for the kappa coefficient was 0.36 – 0.84, which possibly results in low intra-tester reliability when scoring this item separately. This might be the result of subjective anatomical reference determination in Kinovea. It is advised to mark both ASIS reference points with tape to aid scoring of this item.

The results are in agreement with Piva et al.[19] They evaluated a lateral step down on 5 items and depending on the movement deviation severity, 1 or 2 points were added per item and, based on the total scores, participants were classified as having poor (score 4-10), medium (score 2-3) or good quality (score 0-1) of movement. However, reliability was calculated on the aggregate score without taking into account the separate items. This could result into reliably classifying two participants as having the same quality of movement, whilst having very dissimilar test performances. Furthermore, their test was designed to detect altered movement patterns in patients with patellofemoral pain syndrome. It is possible that the step down height (*20 cm*) in their study was not physically demanding enough to identify inadequate neuromuscular control in healthy subjects. Therefore, the step down height for the current study was adjusted to 30 cm as proposed by Norcross et al.[17] Chmielewski et al.[2] did not find high agreement between raters for scoring the lateral step down test. They scored excessive, moderate, small or no movement deviation from the neutral position for the trunk, pelvis and hip during a similar test protocol. These less than favorable results were attributed to the absence of explicit scoring guidelines for the examiners and a timed scoring period of 30 seconds after viewing the test performance.

The protocol for the lumbopelvic position-reposition test was based on the study of Stevens et al.[23] However, they evaluated repositioning capacities based on ultrasound 3D movement analysis, which was reliable but its use in clinical practice is limited. Therefore, in our study, four different items were developed to quantify repositioning capacities of the trunk and lumbopelvic region.

Based on the ICC value (and 95% CI) of the aggregate scores on the lumbopelvic position-reposition test, moderate to excellent reliability can be expected for the evaluation of the test. Substantial agreement was found for the intra- and inter-tester reliability for the separate items 'position of the pelvis' and 'lumbar spine curvature', with all kappa coefficients for these items obtaining clinically acceptable agreement. On the other hand, only fair to substantial agreement was found for the items 'thoracic spine curvature' and 'inclination of the thorax' of which only intra-tester reliability for 'inclination of the thorax' obtained clinically acceptable agreement. Although acceptable reliability can be expected when using the aggregate score, it is not recommended to use the lumbopelvic position-reposition test and its scoring method in the current form. Agreement for the items 'thoracic spine curvature' and 'inclination of the thorax' is not clinically acceptable, especially when multiple examiners are used for comparing test scores. If the same examiner performs scoring, acceptable agreement can be expected. However, taken into account the 95% CI, it is warranted for future research to adjust the scoring method in order to improve agreement on these separate items. More specific criteria, combined with the use of Kinovea could improve the scoring and the agreement for these two items.

With each test taking less than 10 minutes to perform and score, no extra costs attached, simple training needed and detailed operating instructions for scoring readily available, both tests are considered as clinically feasible.[25]

A few methodological considerations need to be taken into account. First, it should be noted that only two raters were used to perform inter-tester reliability since using three or more raters should provide a better representation of the reliability. However, in a similar study, Chmielewski et al.[2] found comparable results when calculating reliability coefficients for two raters and three raters. Second, anatomical reference points were used for measuring angles and quantifying movement deviations during the lateral step down test with Kinovea. However, no markers were used during test performance to indicate these reference points. Nonetheless, reliable results were yielded when using the current method of determining anatomical reference points to evaluate movement deviations except for the item 'pelvic control'. Using tape to mark anatomical reference points might improve reliability for this item.

5 Conclusion

Scoring the lateral step down test with video analysis and the software program Kinovea is reliable. This test can be performed and scored in clinical practice to evaluate trunk and lumbopelvic neuromuscular control in a healthy population. On the contrary, scoring the lumbopelvic position-reposition test using the novel scoring method is not recommended for use in clinical practice due to low inter-tester agreement on two items. Future research should focus on defining more specific criteria to score the items 'thoracic spine curvature' and 'inclination of the thorax' for this test. Furthermore, investigating concurrent validity for both tests is warranted and could be executed with 3D video analysis. As such, the performance quality of the separate items can be compared against criterion standards.

References

1. Brouwer S, Reneman MF, Dijkstra PU, et al. Test-retest reliability of the Isenhargen work systems functional capacity evaluation in patients with chronic low back pain. *J Occup Rehab.*2003;13(4):207-218.
2. Chmielewski TL, Hodges MJ, Horodyski M, et al. Investigation of clinician agreement in evaluating movement quality during unilateral lower extremity functional tasks: a comparison of 2 rating methods. *J Orthop Sports Phys Ther.* 2007;37(3):122-129.
3. Cicchetti DV, Sparrow SA. Developing criteria for establishing interrater reliability of specific items: applications to assessment of adaptive behavior. *Am J Ment Defic.* 1981;86(2):127-137.
4. Comerford MJ, Mottram SL. Movement and stability--contemporary developments. *Man Ther.* 2001;6(1):15-26.
5. Danneels L, Coorevits P, Cools A, et al. Differences in electromyographic activity in multifidus muscle and the iliocostalis lumborum between healthy subjects and patients with subacute and chronic low back pain. *Eur Spine J.* 2002;11(1):13-19.
6. Evans K, Refshauge KM, Adams R. Trunk muscle endurance tests: reliability, and gender differences in athletes. *J Sci Med Sport.* 2007;10(6):447-455.
7. Hayen A, Dennis RJ, Finch CF. Determining the intra- and inter-observer reliability of screening tools used in sports injury research. *J Sci Med Sport.* 2007;10(4):201-210.
8. Hewett TE, Paterno MV, Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop Relat Res.* 2002;402:76-94.
9. Hollman JH, Ginos BE, Kozuchowski J, et al. Relationship between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. *J Sport Rehabil.* 2009;18(1):104-117.
10. Hunt DG, Zuberbier OA, Kozlowski AL et al. Reliability of the lumbar flexion, lumbar extension, and passive straight leg raise test in normal populations embedded within a complete physical examination. *Spine (Phila Pa 1976).* 2001;26(24):2714-2718.
11. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-198.
12. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropr Med.* 2016;15(2):155-163.
13. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics.* 1977;33(1):159-174.
14. Leetun DT, Ireland ML, Willson JD, et al. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc.* 2004;36(6):926-934.
15. Lust KT, Sandrey MA, Bulger SM, et al. The effect of 6-week training programs on throwing accuracy, proprioception, and core endurance in baseball. *J Sport Rehabil.* 2009;18(3):407-426.
16. Nomden JG, Slagers AJ, Bergman GJD, et al. Interobserever reliability of physical examination of the shoulder girdle. *Man Ther.* 2009;14(2):152-159.
17. Norcross M, Halverson SD, Hawkey TJ, et al. Evaluation of the lateral step-down test as a clinical assessment of hip musculature strength. *Athl Train Sports Health Care.* 2009;1(6):272-278.
18. Oliveira IO, Pilz B, Santos RLG Junior, et al. Reference values and reliability for lumbopelvic strength and endurance in asymptomatic subjects. Braz J Phys Ther. 2018;22(1):33-41.
19. Piva SR, Fitzgerald K, Irrgang JJ, et al. Reliability of measures of impairments associated with patellofemoral pain syndrome. *BMC Musculoskelet Disord.* 2006;7:33.
20. Rabin A, Kozol Z. Measures of range of motion and strength among healthy women with differing quality of lower extremity movement during the lateral step-down test. *J Orthop Sports Phys Ther.* 2010;40(12):792-800.
21. Sahrmann S, Azevedo DC, Dillen LV. Diagnosis and treatment of movement system impairment syndromes. Braz J Phys Ther. 2017;21(6):391-399.
22. Smart KM, Curley A, Blake C, et al. The reliability of clinical judgements and criteria associated with mechanisms-based classifications of musculoskeletal pain in patients with low back pain disorders: a preliminary reliability study. *J Man Manip Ther.* 2010;18(2):102-110.
23. Stevens VK, Bouche KG, Mahieu NN, et al. Reliability of a functional clinical test battery evaluating postural control, proprioception and trunk muscle activity. *Am J Phys Med Rehabil.* 2006;85(9):727-736.

24. Thomas JR, Nelson JK, Silverman S. *Research methods in physical activity. 7th ed*. Champaign, Illinois: Human Kinetics Publishers; 2015.
25. Tyson SF, Brown P. How to measure fatigue in neurological conditions? A systematic review of psychometric properties and clinical utility of measures used so far. *Clin Rehabil*. 2014;28(8):804-816.
26. Verrelst R, De Clerq D, Vanrenterghem J, et al. The role of proximal dynamic joint stability in the development of exertional medial tibial pain: a prospective study. *Br J Sports Med*. 2013;48(5):388-393.
27. Walter SD, Eliasziw M, Donner A. Sample size and optimal designs for reliability studies. *Stat Med*. 1998;17(1):101-110.
28. Wilkerson GB, Giles JL, Seibel DK. Prediction of core and lower extremity strains and sprains in collegiate football players: a preliminary study. *J Athl Train*. 2012;47(3):264-272.
29. Zazulak BT, Cholewicki J, Reeves NP. Neuromuscular control of trunk stability: clinical implications for sports injury prevention. *J Am Acad Orthop Surg*. 2008;16(9):497-505.
30. Zazulak BT, Hewett TE, Reeves NP, et al. The effects of core proprioception on knee injury. *Am J Sports Med*. 2007;35(3):368-337.

Appendix

Table 1 Scoring method used for the lateral step down test and the lumbopelvic position-reposition test

Point value	Lateral step down test			Total score
	Dynamic balance	**Knee valgus/HIR**	**Pelvic control**	
0	Large movement of trunk or free leg	Patella medial to hallux	ASIS angle ≥ 20°	/9
1	Moderate movement of trunk or free leg	Patella straight above hallux	ASIS angle between 10° and ≤ 20°	
2	Small movement of trunk or free leg	Patella on hip-MT2 line (oscillations)	ASIS angle between 0° and ≤ 10°	
3	No movement of trunk or free leg	Patella on hip-MT2 line (no oscillations)	ASIS on the same level	

Point value	Lumbopelvic position-reposition test				Total score
	Position of the pelvis	**Lumbar spine curvature**	**Thoracic spine curvature**	**Inclination of the thorax**	
0	Impossible to reposition	Impossible to reposition	Large deviation	Large deviation	/10
1	Large deviation	Large deviation	Small deviation	Small deviation	
2	Small deviation	Small deviation	Perfect repositioning	Perfect repositioning	
3	Perfect repositioning	Perfect repositioning	NA	NA	

ASIS: Anterior superior iliac spine; HIR: Hip Internal Rotation; MT2: Metatarsal 2; NA: not applicable

2

Table 3 Intra-tester and inter-tester reliability of the lateral step down test and lumbopelvic position-reposition test (ICC values, based on the aggregate test scores, with corresponding SEM values and MDC values)

	N	ICC (2,1)	95% CI for ICC	SEM*	MDC*
Intra-tester reliability Lateral step down Test	30	0.88	0.76 – 0.94	0.44	1.23
Inter-tester reliability Lateral step down Test	30	0.81	0.64 – 0.9	0.51	1.42
Intra-tester reliability Lumbopelvic position-reposition test	30	0.87	0.75 – 0.94	0.64	1.76
Inter-tester reliability Lumbopelvic position-reposition test	30	0.73	0.51 – 0.86	0.85	2.34

CI = confidence interval; MDC = Minimal Detectable Change; N = number of subjects; SEM = standard error of measurement. *SEM values and MDC values are represented on a scale from 0-9 for the lateral step down test; on a scale from 0-10 for the Lumbopelvic position-reposition test.

Table 4 Intra-tester and inter-tester reliability of the different items of the lateral step down test and the lumbopelvic position-reposition test (Linear weighted kappa coefficients, with percentage agreement between examiners for each item scored)

Lateral step down Test	N	Kappa	95% CI for Kappa	% agreement
Intra-tester reliability Dynamic balance	30	0.81	0.66 – 0.97	83.3
Intra-tester reliability Knee valgus/HIR	30	0.91	0.74 – 1	96.7
Intra-tester reliability Pelvic control	30	0.62	0.36 – 0.84	76.7
Inter-tester reliability Dynamic balance	30	0.65	0.45 – 0.85	70
Inter-tester reliability Knee valgus/HIR	30	0.75	0.51 – 0.98	90
Inter-tester reliability Pelvic control	30	0.78	0.57 – 0.99	86.7
Lumbopelvic Position-Reposition Test	**N**	**Kappa**	**95% CI for Kappa**	**% agreement**
Intra-tester reliability Position of the pelvis	30	0.62	0.39 – 0.86	70
Intra-tester reliability Lumbar spine curvature	30	0.76	0.56 – 0.96	83.3
Intra-tester reliability Thoracic spine curvature	30	0.5	0.19 – 0.81	70
Intra-tester reliability Inclination of the thorax	30	0.7	0.47 – 0.94	83.3
Inter-tester reliability Position of the pelvis	30	0.61	0.32 – 0.87	80
Inter-tester reliability Lumbar spine curvature	30	0.72	0.49 – 0.95	83.3
Inter-tester reliability Thoracic spine curvature	30	0.29	0.01 – 0.57	60
Inter-tester reliability Inclination of the thorax	30	0.25	0.01 – 0.55	56.7

CI = confidence interval; HIR: Hip Internal Rotation; N = number of subjects

CHAPTER III

THE ROLE OF CORE STABILITY IN THE DEVELOPMENT OF LOWER EXTREMITY INJURIES

PART I

Impaired core stability as a risk factor for the development of lower extremity overuse injuries: a prospective study

Cedric De Blaiser[1], Roel De Ridder[1], Tine Willems[1], Luc Vanden Bossche[1], Lieven Danneels[1], Philip Roosen[1]

[1] *Department of Rehabilitation Sciences, Ghent University, 9000 Ghent, Belgium*

First round revision for the American Journal of Sports Medicine, 2018

Abstract

Objectives: Core stability has been suggested to influence lower extremity functioning and might contribute to the development of lower extremity overuse injuries, but prospective studies to investigate this relationship are limited. The objective of this study is to investigate the role of different components of core stability as risk factors for the development of lower extremity overuse injuries.

Methods: 142 first-year physical education students participated in this study. They were tested in 2015 and were prospectively followed for maximally 1.5 years by means of a multilevel injury registration method. Three participants were excluded due to physical complaints during testing. As such, 139 participants were included in the statistical analysis. At baseline, dynamic postural control, isometric core and hip muscle strength, core muscle endurance, core neuromuscular control and proprioception and functional movement were measured in all participants. Competing risk regression analyses was performed to identify significant contributors to the development of lower extremity overuse injuries.

Results: During the follow-up period, 34 of the 139 participants developed a lower extremity overuse injury (25%). Significant predictive effects for an overuse injury were found for an increased side-by-side difference in dynamic postural control (P = .038), decreased isometric hip extension/flexion strength ratio (P =.046) and decreased abdominal core muscle endurance (P = .032).

Conclusion: This study identified measures for dynamic postural control, core muscle strength and core muscle endurance as significant risk factors for the development of overuse injuries after statistical model building. On the other hand, core neuromuscular control, core proprioception and functional movement might not allow clinicians to identify subjects at risk. These accessible, reliable screening tools could be used in clinical practice with regards to screening and injury prevention for overuse injuries.

Keywords: Core muscle strength, core muscle endurance, postural control, injury prevention, injury screening, lower extremity overuse injuries

1 Introduction

Core stability is considered an essential concept in clinical rehabilitation and athletic training.[8] It is generally defined as the foundation of dynamic control of the lumbopelvic hip complex that allows for optimal production, transfer and control of force and motion, which is transferred throughout the kinetic chain during functional movement.[35,36] Adequate core stability ensures safe and controlled movement distal to the core, and is considered an important contributor in maintaining dynamic joint stability in the kinetic chain.[35,36] From an anatomical point of view, the musculoskeletal core of the body refers to the osseous and soft tissue structures of the spine, pelvis, hip and the abdomen.[6,8,36] Core stability relies on different musculoskeletal capacities for efficient functioning.[9,22,30,34,37] It requires substantial core muscle endurance, strength, proprioception and neuromuscular control.

Deficiencies in any of these components of core stability may affect performance and increase susceptibility for musculoskeletal injury since core stability provides dynamic joint stability. For example, impaired core stability has been suggested to contribute to the development of low back pain.[8,10,28,45] In addition, core stability can be considered a proximally located contributor to lower extremity injuries.[11,36] A significant share of lower extremity injuries are overuse injuries and are traditionally defined as injuries that occur with gradual onset over time and are thought to be the predominant injury type as a result of repetition of similar technical movement patterns such as jumping, landing and cutting.[4,39] The etiology of overuse injuries remains largely unknown,[48] and local intrinsic factors have already been suggested.[41,51,52] Core stability, as a non-local risk factor, could have a crucial role in developing lower extremity overuse injuries since inadequate core stability is believed to increase uncontrolled joint displacements or accessory movements throughout the kinetic chain and could therefore increase susceptibility for the development of overuse injuries.[11,49,50]

3

However, based on current literature, there seems to be limited proof for core stability and its role in the development of lower extremity overuse injuries.[18] Furthermore, there is no single measure for determining core stability since it relies on different musculoskeletal capacities and, measurements to assess core stability often depend upon lab testing or expensive methods.[49,54] As such, the lack of transparency in the concept of core stability as a risk factor and, the lack of a single valid and reliable assessment method to comprehensively evaluate different aspects of core stability have led to suboptimal implementation of the assessment of core stability as a preventative screening tool in clinical practice. Therefore, the aim of this prospective study was to investigate the different components, necessary for adequate core stability as possible risk factors in the development of lower extremity injuries in an active population. These components include dynamic postural control, core neuromuscular control and proprioception, core muscle strength and core muscle endurance and functional movement.

2 Methods

2.1 Study Design

A prospective cohort study was set up with a 1.5 year follow up period. At the start of the 2015-2016 academic year, all participants performed a core stability test battery to assess dynamic postural control, core neuromuscular control and proprioception, core muscle strength and core muscle endurance in a standardized order. Prior to the tests, participants completed a questionnaire with regards to demographic and anthropometric data, sports activities, and injury history. Injury registration was performed for the following 1.5 years. This study was approved by the local university hospital Ethics Committee.

2.2 Participants

150 freshmen students, enrolled in the physical education *studies* of the Artevelde University College Ghent (115) and the University College Ghent (35) were recruited. The physical education study program consists of weekly intracurricular, co-educational sports classes including swimming, athletics, dance, gymnastics, racket sports, basketball, soccer and volleyball. Participants were excluded if they had a history of surgery of the lower extremity. They were also excluded if they reported an injury of the lower extremity/low back in the past 6 months prior to testing, if they had a history of low back pain or if they reported musculoskeletal complaints at the start of the study. Eight subjects did not fulfill those criteria which resulted in 142 included participants (109 male and 33 female). Participants gave their written informed consent prior to participation.

2.3 Injury Registration and Diagnostic Criteria

A multilevel registration method and predetermined criteria were used to detect lower extremity overuse injuries of interest. A primary online registration method, which consisted of a weekly online questionnaire, was used to identify participants with a potential lower extremity overuse injury. Secondly, every 3 months, participant interviews were conducted via contact by phone to check compliance with the injury registration and to verify physical complaints and minor insults during the past 3 months. Diagnosis of the overuse injury was performed by the participants own general practitioner or sports physician and was confirmed by the main researcher based on information on physical complaints, the onset and the mechanism of the injury. Overuse injuries were considered the result of cumulative trauma or repetitive use and stress and,[53] predetermined criteria for an injury to be classified as an overuse injure were used in accordance with current literature. In general, any lower extremity injury without a specific, clearly identifiable injury event (regardless of whether the insidious injury onset was gradual or rapid), which resulted in functional limitation during physical activity or sports was considered an overuse injury[4,21,27] All other injuries were considered as being acute. A distinction was made between overuse tendon injuries and overuse muscle injury. The latter were described as a gradual injury to the muscle belly not as a result of (1) a sudden large direct, compressive force, resulting in contusion or lesion or (2) if the muscle was subject to an acute excessive tensile force, resulting in strain or rupture.

2.4 Exposure time

The average weekly sports participation (sum of active sports education, practice hours, and active sports participation outside of the official educational program) was registered and, this total amount of active sports participation was individually used as time at risk. The time at risk for each individual participant was calculated from the start of the study until the occurrence of a lower extremity injury, or until the end of the study for students who developed an injury not located at the lower extremity or those who did not develop an injury at all.

2.5 Core stability testing

Dynamic Postural Control

The star excursion balance test (SEBT), as described by Plisky et al[44] was performed as a measure for single-leg dynamic postural control. The farthest distance of three trials for the anterior, posterior medial and posterior lateral reach direction was normalized to leg length and was used for analysis.[29] A composite score was calculated for the overall performance on the test and absolute differences between the left and the right leg for each direction were calculated since these parameters have already been shown to be an indicator for lower extremity injury.[44]

Core Muscle Strength

Handheld dynamometry was used to assess maximal isometric hip and trunk muscle strength. Hip muscle strength tests were performed for hip adductor, abductor, external rotator, internal rotator, flexor and extensor muscles. The tests were performed as described by Thorberg et al.[47] Isometric trunk muscle strength was performed by handheld dynamometry for trunk flexion and trunk extension strength as described by De Blaiser et al.[16] One submaximal trial was allowed for each muscle group and three maximal repetitions were used for data analysis. All tests were performed using a MicroFET 2 handheld dynamometer (Hoggan Scientific LLC, Salt Lake City). The test order for the hip and trunk muscle strength testing was randomized to avoid systematic bias.

Core Muscle Endurance

Three different isometric trunk holding tests were implemented in order to evaluate core muscle endurance. The prone bridging test was used to measure abdominal muscle endurance capacity,[18] the Biering-Sørensen test, as described by Coorevits et al,[14] was used to measure back muscle endurance. Last, the side bridging test, as described by McGill et al[42] was used to measure lateral core muscle endurance capacities and was performed bilaterally.

Neuromuscular Control and Proprioception of the Core

Core neuromuscular control was assessed with a test that evaluates a repeated lumbopelvic movement on five categories; quality of the lumbopelvic motion, control of the adjacent areas, preference of motion direction, breathing, and the amount of good quality repetitions. The test was performed as described by Elgueto-Cancina et al.[23] The lumbopelvic movement performance was filmed in the sagittal plane with a standard video camera (Canon Legria hfG10, Canon Inc., Tokyo, Japan; 25 frames/second) and the five criteria were evaluated afterwards using a rating scale, resulting in an aggregate score on 10 points with a higher score signifying better neuromuscular control of the thoracolumbar and lumbopelvic region.

Proprioception of the core was evaluated with a repositioning test that evaluates the participant's repositioning accuracy of the pelvis, low back and trunk after a dynamic task.[17] The position-repositioning test was filmed in the sagittal plane with a standard video camera (Canon Legria hfG10, Canon Inc., Tokyo, Japan; 25 frames/second) and was evaluated afterwards. Four criteria (position of the pelvis, lumbar spine curvature, thoracic spine curvature and, inclination of the thorax) were scored using a rating scale, resulting in an aggregate score on 10 points with a higher score signifying better lumbopelvic proprioception capacities.

Functional Movement Assessment

Dynamic trunk, lumbopelvic and lower extremity movement control was evaluated bilaterally with the lateral step down test.[17] For this test, the participant stood on the edge of a box in unipodal stance and was asked to perform 5 consecutive lateral step downs. The performance was filmed in the frontal plane using a standard video camera (Canon Legria hfG10, Canon Inc., Tokyo, Japan; 25 frames/second) and scoring of the test was performed afterwards based on the movement pattern of the trunk, pelvis and lower extremity during the step down. This resulted in an aggregate score on 9 points with a higher score signifying better dynamic movement control.

2.6 Statistical Analyses

Data from the injured leg of the participants who developed a lower extremity overuse injury was used in the statistical analysis together with the data from the control group. If a participant developed bilateral symptoms, only the more painful leg, based on a visual analog scale, was included. The dominance ratio (dominant leg/non-dominant leg ratio) was matched between the control and the injured group. As such, 1 leg per participant of the control group was randomly selected according to the dominance ratio in the injured group (Figure 1). Statistical analysis was conducted with R statistics (R Version 3.4.4). Lower extremity overuse injuries were the injuries of interest and bilateral injuries and lower extremity injuries other than overuse injuries were included in the regression analysis as competing risks.[26] First, univariate competing risk regression analyses were performed allowing reduction of the number of variables since variables were only included for further analysis if $P < .2$. Second, stepwise multivariate competing risk regression analyses were performed to identify significant contributors to the development of overuse injuries while correlations were checked between covariates to exclude multicollinearity. Generalized Akaike Information Criteria (AIC) were calculated for the different stepwise multivariate models, with the lowest AIC indicating the best predictive model.[1] Variables with a $P < .05$ in the multivariate model were seen as significant predictors for overuse injuries. Receiver Operating Characteristic (ROC) curve analysis was performed in order to determine the optimal sensitivity versus specificity balance and the corresponding cut-off value for predicting high versus low risk subjects based on the best predictive model.

Goodness-of-fit tests for Fine and Gray subdistribution hazards models were performed based on the cumulative sums of residuals which validate the model in three aspects: 1) proportionality of hazard ratio, 2) the linear functional form and 3) the link function.[38]

3 Results

Validity and reliability for all tests used in this study has been established in previous research.[14,16-18,23-25,29,43] Three participants experienced physical discomfort during testing and were excluded. As such, 139 participants, with a mean age of 19.5 ± 1.4 were considered for statistical analysis. The sports performed by the participants outside of the physical education studies were registered and included soccer (53), basketball (15), volleyball (7), athletics (10), gymnastics (10), dance (3), swimming (6) martial arts (5), racket sports (3), cycling (4), power training (12) and other sports (11). A total of 34 (25%) of the 139 included participants developed lower extremity overuse injuries during the 1.5 year follow-up period

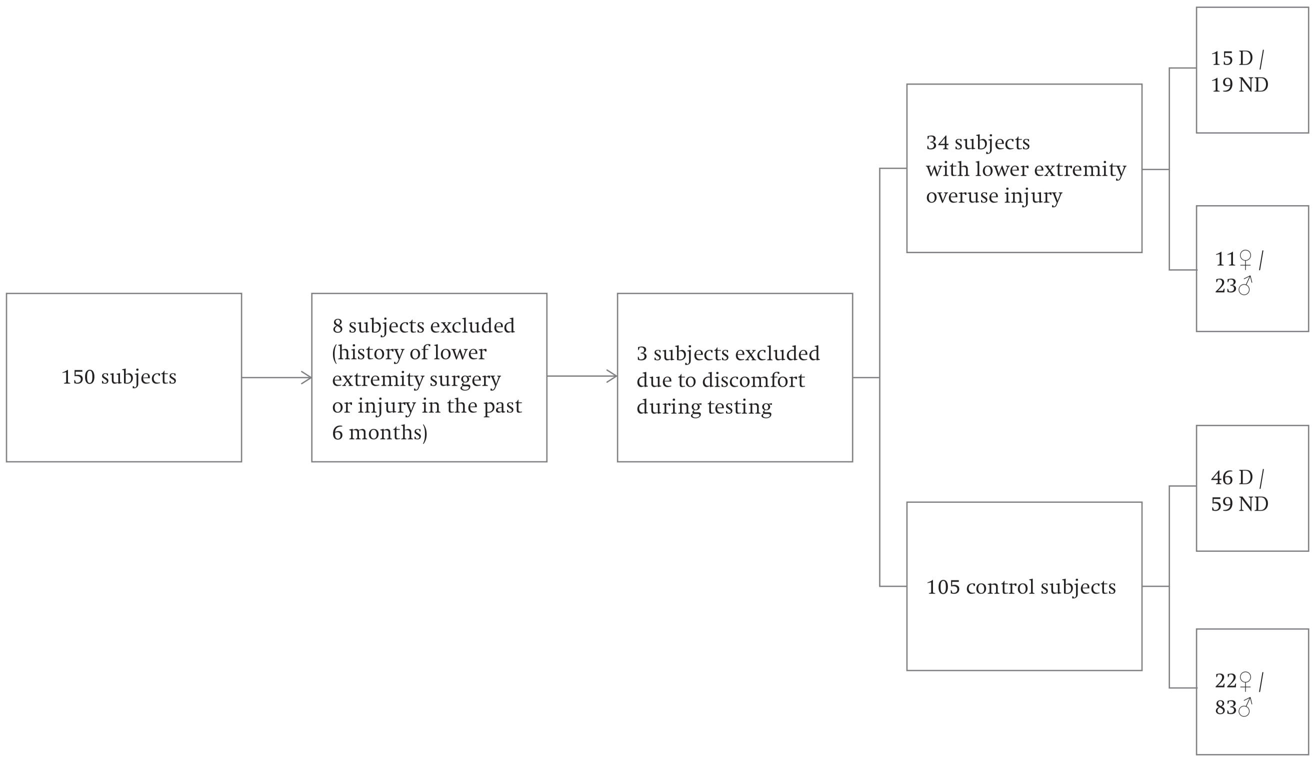


Figure 1 Flowchart for identification of the injured group and the randomly selected dominance-matched control group.

D = Dominant; ND = Non-dominant

and the remaining 104 (75 %) participants who did not sustain an overuse injury of the lower extremity served as the control group (Figure 1). The injury rate for lower extremity overuse injury was 0.6 events per 1000 hours of active sports participation. An overview of the type of lower extremity overuse injury and location is presented in Table1.

Table 1 Summary of overuse injuries per gender (n)

	Male (22/34)	**Female (12/34)**
Hip	Gluteal muscle tendinopathy (2)	Iliopsoas syndrome (1)
Thigh	Adductor tendinopathy (2) Hamstring muscle overuse injury (3) Hamstring tendinopathy (proximal) (2)	Adductor muscle overuse injury (1) Adductor tendinopathy (1) Quadriceps muscle overuse injury (1)
Knee	Patellar tendinopathy (3) Quadriceps tendinopathy (1)	Patellar tendinopathy (1) Patellofemoral pain syndrome (1) Quadriceps tendinopathy (1)
Lower leg	Calf muscle overuse injury (4) Exertional medial tibial pain syndrome (3)	Long peroneal muscle tendinopathy (1) Exertional medial tibial pain syndrome (3)
Ankle/Foot	Achilles tendinopathy (2)	Achilles tendinopathy (1)

Competing Risk Regression Analysis

Subject characteristics and test outcome measures which after univariate competing risk analysis are reported in Table 2.

After multivariate model building, the final model included the variables: left leg/right leg reach difference in the anterior direction, hip extension/flexion strength ratio, abdominal core muscle endurance and female gender. Although it did not have a significant predictive effect on the development of overuse injuries, gender was taken into account in the final model as a confounder due to an uneven distribution of gender in the overuse injury group compared to the control group and the significant differences between male and female subjects for several core muscle strength and endurance variables. A good model fit was ascertained based on the goodness-of-fit tests. The results of the multivariate competing risk regression analysis and risk factor strength is presented in Table 3. The multivariate competing risk regression analysis showed a predictive effect for measures of dynamic postural control, core muscle strength and core muscle endurance. A bigger imbalance in left/right postural control, a lower hip extension/flexion strength ratio and lower abdominal core muscle endurance were considered as risk factors for developing a lower extremity overuse injury. The hazard of developing such injury increased with 12% if the absolute left/right anterior reach distance during the SEBT

Table 2 Subject Characteristics and Test Outcome Measures for the Control Group and the Overuse Injury (OI) Group

Subject Characteristics and Test Outcome Measures[a]	Control Group[b] (n = 105)	OI Group[b] (n = 34)	P Value[c]
Age, y	19.49 ± 13.37	19.64 ± 1.38	.5
Height, m	1.77 ± 0.07	1.75 ± 0.08	.25
Weight, kg	69.46 ± 9.51	68.22 ± 9.79	.64
Body mass index, kg/m²	22.07 ± 2.3	22.18 ± 2.21	.75
Gender, n (%)			.23
Male	83/105 (79%)	23/34 (68%)	
Female	22/105 (21%)	11/34 (32%)	
Dominance, n (%)			.9
Dominant leg	46/105 (44%)	15/34 (44%)	
Non-dominant leg	59/105 (56%)	19/34 (56%)	
Sports participation at baseline, hours/week	17.5 ± 5.22	17.08 ± 3.99	.68
Main sport (outside of physical education sports activity)			.5
Dynamic postural control			
Normalized anterior reach distance, cm/leg length (m)	65.56 ± 5.85	65.4 ± 6.21	.97
Normalized posterior medial reach distance, cm/leg length (m)	102.95 ± 7.96	101.98 ± 8.15	.47
Normalized posterior lateral reach distance, cm /leg length (m)	97.29 ± 8.89	95.3 ± 8.5	.19
Composite score, cm/leg length (m)	93.59 ± 8.49	93.43 ± 10.42	.83
Reach distance L/R difference (anterior), cm [1]	2.66 ± 2.12	3.47 ± 2.89	.043*
Reach distance L/R difference (posterior medial), cm [1]	4.66 ± 3.69	5.44 ± 2.76	.18
Reach distance L/R difference (posterior lateral), cm [1]	5.49 ± 4.33	4.27 ± 2.63	.062
Core muscle strength			
Trunk extension strength, N/kg [2]	6.1 ± 1.29	5.7 ± 1.25	.091
Trunk flexion strength, N/kg [3]	3.61 ± 0.87	3.23 ± 0.81	.025*

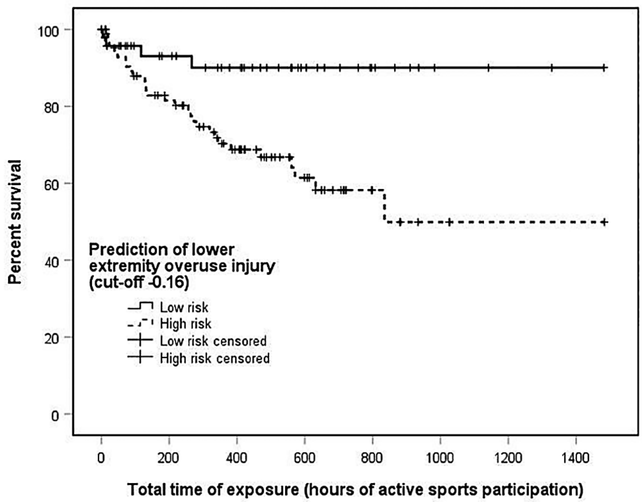
Hip extension strength, N/kg [2]	4.36 ± 1.16	3.76 ± 0.89	.004*
Hip flexion strength, N/kg [2]	5.58 ± 0.85	5.3 ± 0.98	.16
Hip abduction strength, N/kg [2]	5.12 ± 0.92	4.99 ± 1.13	.53
Hip adduction strength, N/kg [2]	3.78 ± 0.65	3.66 ± 0.67	.43
Hip internal rotation strength, N/kg [4]	2.46 ± 0.68	2.26 ± 0.75	.18
Hip external rotation strength, N/kg [3]	2.12 ± 0.47	1.9 ± 0.49	.031*
Trunk extension/flexion strength ratio, (N/kg)/(N/kg) [3]	1.77 ± 0.47	1.83 ± 0.46	.59
Hip extension/flexion strength ratio, (N/kg)/(N/kg) [2]	0.78 ± 0.16	0.71 ± 0.15	.034*
Hip adduction/abduction strength ratio, (N/kg)/(N/kg) [2]	0.75 ± 0.13	0.75 ± 0.12	.99
Hip IR/ER strength ratio, (N/kg)/(N/kg) [4]	1.18 ± 0.24	1.2 ± 0.3	.73
Core muscle endurance			
Prone bridging test, s [1]	121.6 ± 60.9	94.9 ± 36.1	.007*
Biering-Sørensen test, s [2]	125 ± 39.7	113.5 ± 30.2	.093
Side bridging test, s	90.7 ± 37.8	75.3 ± 26.3	.025*
Core neuromuscular control			
Lumbopelvic control test (total score) [3]	5.6 ± 1.85	5.9 ± 1.85	.26
Core proprioception			
Lumbopelvic position-reposition test (total score) [7]	7.04 ± 1.7	6.47 ± 1.6	.098
Functional Movement Assessment			
Lateral step down test (total score)	5.3 ± 1.4	5.4 ± 1.3	.62

L/R = Left/Right; N/kg = Newton/kilogram bodyweight; IR/ER = Internal rotation/External rotation
*Indicates significance at the $p < 0.05$ level
[a]Brackets indicate the number of missing values
[b]Outcome measures expressed as mean ± SD or n (%)
[c]*P* values obtained by univariate competing risk regression analysis.

Table 3 Risk Model Obtained by Competing Risk Regression for the Prediction of Lower Extremity Overuse Injury Versus No Injury

Indicator	β	SE	P Value	Hazard Ratio	95% Confidence Interval
Left leg/right leg anterior reach distance difference	0.109	0.052	.038*	1.115	1.006-1.236
Hip extension/flexion strength ratio	-2.263	1.132	.046*	0.104	0.011-0.957
Abdominal core muscle endurance	-0.007	0.003	.032*	0.993	0.986-0.999
Female gender	0.326	0.381	.39	1.386	0.657-2.924

*Indicates significance at the $p < .05$ level



Number of events / Number at risk								
TTE (h)	0-200	200-400	400-600	600-800	800-1000	1000-1200	1200-1400	1400-1600
Low risk	3/47	1/33	0/26	0/15	0/8	0/3	0/2	0/1
High Risk	15/88	9/62	3/42	1/22	1/7	0/3	0/1	0/1

TTE: Total time of exposure (hours of active sports participation)

Figure 2 Kaplan-Meier curve of high and low risk participants with accompanying life table increased with 1 centimeter when other variables are kept constant. Furthermore, the hazard of developing an injury increased with 25% if the hip extension/flexion strength ratio decreased with 0.1 and, the hazard of developing an injury increased with 1% with a decrease of 1 second on the prone bridging test. Prognostic scores were calculated based on the current model. Based on the ROC curve analysis with an area under the curve of 0.707, a cut-off value of -0.16 was determined to classify subjects as being at high or low risk for developing an injury. This model had a predictive accuracy of 53% with a sensitivity of 87.9% and a specificity of 42.2%. A Kaplan-Meier curve of the high-risk group and the low-risk group and the accompanying life table of participants at risk for different amounts of time of exposure is presented in Figure 2.

4 Discussion

This study identified deficits in dynamic postural control, decreased hip muscle flexion/extension strength ratio and lower abdominal core muscle endurance capacities as risk factors for the development of lower extremity overuse injuries after model building with gender taken into account as a confounder. No associations were found between overuse injuries and neuromuscular control, proprioception and the functional movement assessment.

Dynamic Postural Control and Injury Risk

Dynamic balance is reliant on core stability to develop internal muscle moments to counteract the external moments generated by body mass displacement.[13] Furthermore, core stability training has been proven to have a direct effect on dynamic balance and can therefore be considered as a functional measure for core stability.[15] Results of our study revealed an absolute anterior left leg/right leg reach distance difference, as measured in the SEBT, to be significantly associated with an increased hazard to develop an overuse injury. In accordance with the results of our study, Plisky et al[44] established that basketball players with an anterior left leg/right leg reach distance difference greater than 4 cm on the SEBT to be 2.5 times more likely to sustain a lower extremity injury. A side-to-side postural control difference or imbalance could hypothetically influence overuse injuries in different ways.[44] First, imbalance in stability between both legs might alter how a participant reacts to situations in sport activities, causing increased stress to the more adept lower extremity. Second, the more adept lower extremity may absorb excessive force due to instability resulting from poor balance on the less able lower extremity. Finally, the less adept lower extremity may not provide a stable base on which to land or pivot.

Core Muscle Strength and Injury Risk

Hip musculature has been described as an essential contributor for core stability and lower extremity functioning during dynamic movement control.[11] The hips and associated musculature are the base support for core structures and acts in conjunction with lumbopelvic musculature to stabilize the trunk over the lower extremity and generate and transfer force from the pelvis and spine to the leg during athletic activities.[2,36]

Hip muscle strength has been proven to be a risk factor in the development of overuse injuries.[49] However, to the authors' knowledge, this is the first study to prospectively identify isometric hip extension/flexion strength ratio as a risk factor for lower extremity overuse injuries. Values for this ratio in a healthy population have been described in current literature as being close to 1,[40] whereas the overuse injury group in our study exhibited a 0.7 ratio, compared to a ratio of approximately 0.8 in the control group.

For this study, the lower ratio in the injured group was due to significantly lower hip extension strength, compared to the control group. Univariate regression analysis did also identify decreased hip extension strength as a significant predictor an overuse injury but was not withheld in the final model. A possible injury mechanism for decreased isometric hip extension strength, lowered hip flexion/extension strength ratio and injuries was investigated by Teng et al.[46] They described the association between hip extension strength and running kinematics and found a more upright trunk posture during running in participants with decreased isometric hip extension strength resulting in an overreliance on the knee extensors during running which could contribute to altered lower extremity kinematics and possible overuse injuries. Furthermore, De Ridder et al[19] suggested that decreased hip muscle extension strength was associated with reduced dynamic control of the hip and with the reduced capacities of the hip muscles to decelerate the body center of mass during high-velocity athletic maneuvers, resulting in decreased impact absorption during movement.

Univariate regression analysis in our study also revealed other core muscle strength related measures which were associated with overuse injuries. However, these variables were not withheld in the final multivariate model. Among these other variables, decreased isometric hip external rotation strength and decreased isometric trunk flexion strength were also associated with injuries.

Core Muscle Endurance and Injury Risk

Endurance capacity of the trunk extensors has been found to predict low back pain in 30 to 60 year old subjects.[7] On the other hand, conflicting evidence exists in current literature regarding the influence of core muscle endurance and lower extremity injuries. Results of our study indicate decreased endurance capacities of abdominal core musculature and lateral core musculature to be significantly associated to the development of lower extremity overuse injuries. Based on the AIC method and due to high correlation, only abdominal core muscle endurance was withheld in the final model. Contrary to these results, no significant differences were found on hold times for anterior, posterior and lateral core muscle endurance tests in injured compared to uninjured collegiate basketball players and track athletes.[37] Furthermore, none of these measures were considered a risk factor for sustaining an injury. Wilkerson et al[50] also found non-significant differences in endurance times for posterior and lateral core muscle endurance tests in injured compared to uninjured collegiate football players. However, similar to our results, they did find significantly lower endurance times for the anterior endurance test in injured athletes and found reduced anterior core muscle endurance to be a modifiable risk factor for lower extremity injuries. Comparison between studies is difficult since Leetun et al[37] and Wilkerson et al[50] both described general lower extremity injuries and, they both used the flexor endurance test, for which no information is available with regards to validity.[42] Furthermore, the population as described in this study is a multisport cohort in contrast to the aforementioned studies. A possible explanation for an increased risk for lower extremity injury is that suboptimal endurance of the core musculature results in inhibition of specific lower extremity muscles,[30,31] resulting in kinetic and kinematic changes during dynamic tasks, which in turn could predispose a subject to injury.

Core Neuromuscular Control, Proprioception, Functional Movement and Injury Risk

Interestingly, neuromuscular control and proprioception were not associated with the onset of lower extremity overuse injuries. Contrary to the results of our study, inadequate neuromuscular control and proprioception, have been shown to be risk factors for the development of lower extremity injuries since these aspects could compromise dynamic stability and lead to altered movement patterns during locomotion, possibly exposing the lower extremity to injury risk.[49,54,55] Zazulak et al[54] found active repositioning deficits to be a risk factor in the development of knee injuries in female athletes. However, cautious comparison between the results of these studies and our study is necessary since these studies evaluated the aspects of sensorimotor control in lab situations with the use of expensive or not commercially available devices. Furthermore, Zazulak et al[54] only measured trunk proprioception in the transversal plane compared to the sagittal plane in our study. More research is needed to investigate the influence of inadequate neuromuscular control and proprioception on overuse injuries.

This is the first study in which participants performed the functional lateral step down test to assess the relationship between dynamic trunk, lumbopelvic and lower extremity movement control and lower extremity overuse injuries. Results of this test were not associated with an increased risk for developing an injury. However, verification of our results is difficult since no other studies have investigated the relationship between the outcome of this test and lower extremity injuries.

Clinical Implications

The combination of a left leg/right leg anterior reach distance difference, decreased hip flexion/extension strength ratio and decreased abdominal core muscle endurance is a strong predictor for the development of lower overuse injuries. These modifiable intrinsic risk factors are easy to asses with accessible, cost-effective and easy to perform tools in clinical practice for the purpose of lower extremity overuse injury screening. The results of this study suggest that the development and training of adequate postural control, core muscle strength and core muscle endurance should not be neglected with regards to injury prevention. These risk factors could be translated easily into a core stability training program which focuses on dynamic postural control, core muscle strength and endurance. However, further research is needed to investigate whether these easy to train components of core stability have a positive effect on overuse injury incidence.

Methodological Considerations

Several statistical and methodological considerations need to be taken into account when interpreting the results of this study. Previous studies suggested there is a difference between men and women for abdominal muscle endurance capacities and,[42] male and female relative hamstrings to quadriceps strength profiles diverge significantly.[33] Therefore, gender was considered as a confounder in the analysis. The authors are also aware of the relatively limited number of events used to study several core stability variables. As such, a limited number of predictors was included as to not over fit the competing risk regression analysis after the univariate analyses.

Defining overuse injuries in the first place and effectively diagnosing them in the second place is a difficult task.[4] However, the multilevel injury registration method, which relied on a weekly questionnaire to be filled out by the participants, a physician-made diagnosis of all injuries and a three-monthly retrospective personal interview with all participants, allowed for a standardized and comprehensive injury registration system. Last, the authors acknowledge that not all tests, used in current protocol, represent functional movement during sport activities. However, it has been proven difficult to assess one's ability to move through three planes of movement via nontraditional testing in order to receive qualitative and quantitative information related to specialized movement involved in sports and, a frequent issue encountered in using such screening measures is the insufficient reliability, validity and availability of these tests in clinical practice.[32] Therefore, the authors opted to implement easy to use, clinical examination methods which are valid and/or reliable.

5 Conclusion

This is the first prospective study to investigate proximal risk factors, related to core stability, and their association with distally located lower extremity overuse injuries in an active population by using a test battery containing practical screening tools. Imbalance in dynamic postural control between left and right leg, decreased hip flexion/extension strength ratio and decreased core muscle endurance were identified as intrinsic risk factors. Measures of core neuromuscular control, proprioception and dynamic movement control were not significantly associated with lower extremity overuse injuries. Assessment and training of these modifiable risk factor is clinically relevant in injury screening and prevention.

References

1. Akaike H. A new look at the statistical model identification. *IEEE Trans Autom Contr.* 1974;19(6):716-723.
2. Akuthota V, Nadler SF. Core strengthening. *Arch Phys Med Rehab.* 2004;85(1):86-92.
3. Anderson K, Behm D.G. The impact of instability resistance training on balance and stability. *Sports Med.* 2005;35(1):43-53.
4. Bahr R. No injuries, but plenty of pain? On the methodology for recording overuse symptoms in sports. *Br J Sports Med.* 2009;43(13):966-972.
5. Barr KP, Griggs M, Cadby T. Lumbar stabilization: a review of core concepts and current literature, part 2. *Am J Phys Med Rehabil.* 2007;88(1):72-80.
6. Bergmark A. Stability of the lumbar spine. A study in mechanical engineering. *Acta Orthop Scand Suppl.* 1989;230:1-54.
7. Biering-Sørensen F. Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine (Phila Pa 1976).* 1984;9(2):106-119.
8. Borghuis J, Hof AL, Lemmink KA. The importance of sensory-motor control in providing core stability: implications for measurement and training. *Sports Med.* 2008;38(11):893-916.
9. Cholewicki J, McGill SM. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. *Clin Biomech.* 1996;11(1):1-15
10. Cholewicki J, Silfies SP, Shah RA, et al. Delayed trunk muscle reflex responses increase the risk of low back injuries. *Spine (Phila Pa 1976).* 2005;30(23):2614-2620.
11. Chuter VH, Janse de Jonghe XA. Proximal and distal contributions to lower extremity injury: a review of the literature. *Gait Posture.* 2012;36(1):7-15.
12. Clarsen B, Bahr R, Heymans MW, et al. The prevalence and impact of overuse injuries in five Norwegian sports: Application of a new surveillance method. *Scand J Med Sci Sports.* 2015;25(3):323-330.
13. Colston M. Core stability, part 1: Overview of the concept. *Int J Athl Ther Train.* 2012;17(1):8-13.
14. Coorevits P, Danneels L, Cambier D, Ramon H, Vanderstraeten G. Assessment of the validity of the Biering-Sørensen test for measuring back muscle fatigue based on EMG median frequency characteristics of back and hip muscles. *J Electromyogr Kinesiol.* 2008;18(6):997-1005.
15. Cosio-Lima LM, Reynolds KL, Winter C, Paolone V, Jones MT. Effects of physioball and conventional floor exercises on early phase adaptations in back and abdominal core stability and balance in women. *J Strength Cond Res.* 2003;17(4):721-725.
16. De Blaiser C, De Ridder R, Willems T, Danneels L, Roosen R. Reliability and validity of trunk flexor and trunk extensor strength measurements using handheld dynamometry in a healthy athletic population. *Phys Ther Sport.* 2018;34:180-186.
17. De Blaiser C, De Ridder R, Willems T, Danneels L, Roosen R. (in press). Reliability of two functional clinical tests to evaluate trunk and lumbopelvic neuromuscular control and proprioception in a healthy population. *Br J Phys Ther.* https://doi.org/10.1016/j.bjpt.2018.10.014
18. De Blaiser C, De Ridder R, Willems T, et al. Evaluating abdominal core muscle fatigue: Assessment of the validity and reliability of the prone bridging test. *Scand J Med Sci Sports.* 2018;28(2):391-399.
19. De Ridder R, Witvrouw E, Dolphens M, Roosen P, Van Ginckel A. Hip strength as an intrinsic risk factor for lateral ankle sprains in youth soccer players: A 3-season prospective study. *Am J Sports Med.* 2017;45(2):41-416.
20. Diamond LE, Wrigley TV, Hinman RS, et al. Isometric and isokinetic hip strength and agonist/antagonist ratios in symptomatic femoroacetabular impingement. *J Sci Med Sport.* 2016;19(9):696-701.
21. DiFiori JP, Benjamin HJ, Brenner JS, et al. Overuse injuries and burnout in youth sports: a position statement from the American Medical Society for Sports Medicine. *Br J Sports Med.* 2014;48(4):287-288.
22. Ebenbichler GR, Oddson LI, Kollmitzer J, Erim Z. Sensory-motor control of the lower back: implications for rehabilitation. *Med Sci Sports Exerc.* 2001;33(11):1889-1898.
23. Elgueta-Cancino E, Schabrun S, Danneels L, Hodges P. A clinical test of lumbopelvic control: development and reliability of a clinical test of dissociation of lumbopelvic and thoracolumbar motion. *Man Ther.* 2014;19(5):418-424.
24. Elgueta-Cancino E, Schabrun S, Danneels L, van den Hoorn W, Hodges P. Validation of a clinical test of thoracolumbar dissociation in chronic low back pain. *J Orthop Sports Phys Ther.* 2015;45(9):703-712.

25. Evans K, Refshauge KM, Adams R. Trunk muscle endurance tests: reliability, and gender differences in athletes. *J Sci Med Sports*. 2007;10(6):447-455.
26. Fine JP, Gray RJ. A proportional hazards model for the subdistribution of a competing risk. *J Am Stat Assoc*. 1999;94(446):496-509.
27. Fuller CW, Ekstrand J, Junge A, et al. Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Clin J Sports Med*. 2006;41(5):97-106.
28. Gill KP, Callaghan MJ. The measurement of lumbar proprioception in individuals with and without low back pain. *Spina (Phila Pa 1976).* 1998;23(3):371-377.
29. Gribble PA, Hertel J, Plisky P. Using the star excursion balance test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. *J Athl Train*. 2012; 47(3):339-357.
30. Hammill RR, Beazell JR, Hart JM. (2008). Neuromuscular consequences of low back pain and core dysfunction. *Clin Sports Med*. 2008;27(3):449-462.
31. Hart JM, Fritz JM, Kerrigan DC, Saliba EN, Gansneder BM, Ingersoll CD. Reduced quadriceps activation after lumbar paraspinal fatiguing exercise. *J Athl Train.* 2006;41(1):79-86.
32. Hayen A, Dennis RJ, Finch CF. Determining the intra- and inter-observer reliability of screening tools used in sports injury research. *J Sci Med Sport*. 2007;10(4):201-210.
33. Hewett TE, Myer GD, Zazulak BT. Hamstrings to quadriceps peak torque ratios diverge between sexes with increasing isokinetic angular velocity. *J Sci Med Sport*. 2008;11(5):452-459.
34. Hibbs AE, Thompson KG, French D, Wrighley A., Spears I. Optimizing performance by improving core stability and core strength. *Sports Med*. 2008;38(12):995-1008.
35. Ireland ML, Willson JD, Ballantyne BT, Davis IM. (2003). Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther.* 2003;33(11):671-676.
36. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med.* 2006;36(3):189-198
37. Leetun DT, Ireland M, Willson JD, Ballantyne BT, Davis IM. (2004) Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc.* 2004;6(6):926-934.
38. Li J, Scheike TH, Zhang MJ. Checking Fine and Gray subdistribution hazards model with cumulative sums of residuals. *Lifetime Data Anal*. 2015;21(2):197-217.
39. Lian Ø, Engebretsen L, Bahr R. Prevalence of jumper s knee among elite athletes from different sports: A cross-sectional study. *Am J Sports Med.* 2005;33:561–567.
40. Magalhães E, Silva AP, Sacramento SN, Martin RL, Fukuda TY. Isometric strength ratios of the hip musculature in females with patellofemoral pain: a comparison to pain-free controls. *J Strength Cond Res*. 2013;27(8):2165-2170.
41. Mahieu NN, Witvrouw E, Stevens V, Van Tiggelen D, Roget P. Intrinsic risk factors for the development of achilles tendon overuse injury: a prospective injury. *Am J Sports Med*. 2006;34(2):226-235.
42. McGill SM, Childs A, Liebenson C. Endurance times for low back stabilization exercises: clinical targets for testing and training from a normal database. *Arch Phys Med Rehabil*. 1999;80(8):941-944.
43. Mentiplay BF, Perraton LG, Bower KJ, et al. Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: a reliability and validity study. *PLoS One*. 2015;28(10): e0140822.
44. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star excursion balance test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther.* 2006;36(12):911-919.
45. Radebold A, Cholewicki J, Polzhofer GK, Greene HS. Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. *Spine (Phila Pa 1976).* 2001;26(7):724-730.
46. Teng HL, Powers CM. Hip-extensor strength, trunk posture, and use of knee-extensor muscles during running. *J Athl Train*. 2016;51(7):519-524.
47. Thorborg K, Petersen J, Magnusson SP, Hölmich P. Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scand J Med Sci Sports*. 2010;20(3):493-501.
48. van Wilgen CP, Verhagen EA. A qualitative study on overuse injuries: the beliefs of athletes and coaches. *J Sci Med Sport.* 2012;15(2):116-121.
49. Verrelst R, De Clerq D, Vanrenterghem J, Willems T, Palmans T, Witvrouw E. The role of proximal dynamic joint stability in the development of exertional medial tibial pain: a prospective study. *Br J Sports Med.* 2013;48(5):388-393.

50. Wilkerson GB, Giles JL, Seibel DK. Prediction of core and lower extremity strains and sprains in collegiate football players: a preliminary study. *J Athl Train.* 2012;47(30):264-272.
51. Willems TM, De Clercq D, Delbaere K, Vanderstraeten G, De Cock A, Witvrouw E. A prospective study of gait related risk factors for exercise-related lower leg pain. *Gait Posture*. 2006;21(1):91-98.
52. Witvrouw E, Bellemans J, Lysens R, Danneels L, Cambier D. Intrinsic risk factors for the development of patellar tendinitis in an athletic population. A two-year prospective study. *Am J Sports Med*. 2001;29(2):190-195.
53. Yang J, Tibbetts AS, Covassin T, et al. Epidemiology of overuse and acute injuries among competitive collegiate athletes. *J Athl Train*. 2012;47(2):198-204.
54. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk. *Am J Sports Med.* 2007a;35(7):1123-1130.
55. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury. *Am J Sports Med.* 2007b;35(3):368-373.

GENERAL DISCUSSION

1 Summary

The aim of this dissertation was to gain knowledge into the concept of core stability, how it can be assessed and how it is associated with lower extremity injuries (**LEI**). In the general introduction, an overview of the current literature was given in order to understand how stability of the core is established, which components are needed to accomplish core stability and, how these components can be measured in a reliable and/or valid manner. A systematic review on the association between impaired core stability and LEI was performed and, further research was carried out to establish reliability/validity of specific core stability measurement techniques in a healthy population. Finally, the suggested components of core stability were prospectively investigated to establish their role in the development of lower extremity overuse injuries (**LEOI**). A concise summary of the research findings per chapter is presented below.

Limited evidence exists on the association between impaired core stability and lower extremity musculoskeletal injuries. A first step towards gaining insight into this relationship is to research the current available evidence for core stability as a risk factor. Therefore, in **chapter I**, a systematic review of current literature was performed. This systematic review provided preliminary evidence for the association between impaired core stability and the development of LEI in healthy athletes. Limited evidence was found for core strength, core proprioception and neuromuscular control of the core to be potential risk factors in the development of a broad range of LEI. Furthermore, conflicting evidence was found for core endurance as a risk factor for these injuries. Impaired core stability has been suggested to increase susceptibility for the development of overuse injuries through uncontrolled joint displacement or accessory movement during physical activity. However, evidence provided in this systematic review is limited and further research is imperative.

Before performing a prospective study to investigate the association between the different components of core stability and the development of LEOI and to be able to implement these results in clinical practice, there is need for easy to use and reliable and/or valid tests to measure these components of core stability in a healthy population. In **chapter II**, reliable and valid tests to evaluate core muscle endurance, core muscle strength, neuromuscular control and proprioception of the core was investigated to complement the already existing reliable and valid clinical tests. The prone bridging test, a test to measure abdominal core muscle endurance, was found to be reliable and valid based on EMG analysis. Furthermore, measuring trunk flexor and extensor muscle strength using handheld dynamometry (HHD) was also established as a reliable and valid measurement based on comparison with a commercially available isokinetic dynamometer. Finally, reliability for the novel lumbopelvic position-reposition test and the lateral step down test was calculated and were found to be reliable based on the total test score outcomes. On the other hand, it needs to be taken into account that agreement for two out of the four items of the lumbopelvic position-reposition test were not clinically acceptable, especially when multiple examiners are used for comparing test scores. The research performed in chapter II attempted to develop standardized tests, with regards to test protocol and scoring method, for core stability with the transition from a lab setting to a clinical setting in mind. Based on our results, these tests, which evaluate the essential qualities upon which core stability relies, can reliably be used in a clinical practice setting without the use of expensive laboratory equipment.

In **chapter III**, the different components of core stability were prospectively examined to investigate their role in the development of LEOI in a healthy active population. At baseline, isometric trunk and hip muscle strength, core muscle endurance, core neuromuscular control and proprioception were measured with the use of the aforementioned tests. Furthermore, all subjects performed dynamic core stability tests. This study identified measures for dynamic postural control, core muscle strength and core muscle endurance as significant risk factors for the development of overuse injuries. On the other hand, core neuromuscular control, core proprioception and functional movement might not allow clinicians to identify subjects at risk.

2 Main discussion

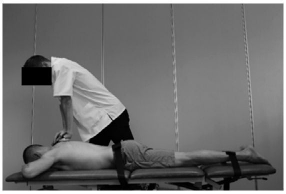
Based on prominent current literature on the topic of core stability and based on own expertise, a working definition and model for core stability was presented in the general introduction. Different anatomical structures were agreed upon as being part of the core and, the separate musculoskeletal components needed in order to achieve core stability (to provide proximal stability for distal mobility) were discussed. Core stability relies on different musculoskeletal capacities for efficient functioning and, achieving core stability requires optimal employment of core muscle strength and endurance, proprioception and neuromuscular control.[3,18,30,46,52,64] Dynamic postural control and functional movement are considered as dynamic products of adequate core stability. In order to discuss the results of the included studies, each component of core stability will be investigated with regards to how it can be measured in clinical practice, what is already known in current literature of its relationship with LEI and finally, how it was prospectively associated with LEOI.

Can core muscle strength be measured in clinical practice and is it associated with lower extremity injuries?

Multiple methods to measure muscle strength and muscle strength characteristics have been described previously.[4,96] Manual muscle testing (MMT), handheld dynamometry (HHD) and isometric or isokinetic muscle testing on a stationary dynamometer can all be performed to evaluate peak muscle force. In the general introduction, core musculature was described as the muscles originating in, and surrounding the abdominal, lumbopelvic and hip regions. Hip and trunk muscle strength measurements using a stationary dynamometer are already established as reliable and valid methods.[34,44,60] The use of stationary dynamometers in clinical practice is rare given its high cost price and low usability. Therefore, MMT and HHD are often suggested for use in clinical practice. However, MMT is considered as not sensitive enough for measuring muscle strength and is highly dependent on the skills and experience of the examiner.[63] Furthermore, evidence for reliability and validity of MMT is lacking to this day.[24] On the other hand, reliability and validity for different hip muscle isometric strength tests using HHD have been established.[75,101] Reliability and validity of HHD for trunk flexor and extensor muscles has not yet been investigated and these strength tests might be influenced by the tester's strength, resistance location, and ability to hold the HHD in a stable position, especially in high force generating muscle groups.[63]

Therefore, in **chapter II, part II,** reliability of trunk flexor and extensor muscle strength using HHD was investigated in a healthy population with a test-retest protocol and, validity was investigated by comparison with a commercially available stationary dynamometer. Excellent intra- and inter-tester reliability was found for two test positions (Table 1). Furthermore, concurrent validity was confirmed based on comparison of peak force values between HHD and the stationary dynamometer. In order to determine whether or not hip flexion/extension musculature is involved in performing these tests, it could be useful in further research to establish construct validity of these tests with the use of sEMG in order to determine the amount of muscle activity of each separate abdominal muscle and to confirm whether or not hip flexor muscle activity is registered during these tests.

Table 1 Intra-tester and inter-tester reliability of the HHD tests for trunk flexor and extensor strength and corresponding SEM values (Nm)

	ICC (2,1)	95% CI for ICC	SEM (Nm)	
Intra-tester reliability Trunk flexion (30°)	0.9	0.8 – 0.95	17.69	
Inter-tester reliability Trunk flexion (30°)	0.93	0.82 – 0.97	16.45	
Intra-tester reliability Trunk extension (0°)	0.93	0.92 – 0.98	14.42	
Inter-tester reliability Trunk extension (0°)	0.76	0.56 – 0.88	20.88	

CI = confidence interval; ICC = Intraclass Correlation Coefficient; SEM = standard error of measurement (Newton meter)

> Reliability and validity to measure isometric hip strength using HHD has already been established. New evidence supports reliability and validity for HHD to measure trunk flexor in a 30° trunk flexion supported supine position and extensor muscle strength in a prone position and, these tests can be used in clinical practice for a healthy population.

The systematic review, described in **chapter I**, established limited evidence for decreased isometric trunk flexor and extensor muscle strength (measured with a HHD) as a risk factor for ACL injuries in male and female ski-racers.[87] Furthermore, the presence of too strong trunk flexors or trunk extensors too weak compared to their antagonists, as indicated by the trunk flexor/extensor strength ratio, was also confirmed as a risk factor for ACL injuries. This study suggested low trunk muscle strength and trunk muscle strength imbalance to be associated with increased knee valgus collapse, leading to an unstable, injury prone knee position during movement.[50,87] This hypothesis is supported by Nakagawa et al.,[77] who found an association between greater isometric trunk muscle strength and lower knee adduction moment during a single leg squat in healthy participants.

The search strategy, as described in chapter I, was recently executed (August 2018) again in order to determine whether there is new evidence for core stability as a risk factor for LEI and the resulting articles were screened similarly as described in chapter I. To date, there is no further evidence that core muscle strength or the core muscles strength ratio is a risk factor for LEI. In chapter III, core muscle strength and strength ratio was prospectively examined in relationship to the development of LEOI due to insufficient evidence in current literature.

In **chapter III**, the relationship between isometric trunk flexion and extension strength, trunk extension/flexion strength ratio and LEOI was prospectively investigated. No significant differences between the injured group and the uninjured group were found for trunk extension strength and trunk extension/flexion strength ratio. On the other hand, significantly lower trunk flexion strength was found in the injured group and, after univariate competing risk analysis only isometric trunk flexion strength could be associated with overuse injuries. However, covariates and confounding variables were not accounted for and this finding should be considered as descriptive since this variable was not withheld after multivariate competing risk analysis. Abdominal strength has previously been associated with maintaining neutral pelvic tilt during a functional task.[78] With increased load, an increase in abdominal muscle activity was established. Therefore, it can be hypothesised that subjects who display low abdominal strength might not be able to maintain lumbopelvic stability during movement, possibly resulting in altered lower extremity kinematics. However, more research is needed to investigate the relationship between low abdominal strength and altered lower extremity kinematics.

In the systematic review of **chapter I**, isolated hip muscle strength was not discussed as a core stability related risk factor for the development of LEI. However, the role of hip muscle functioning in providing core stability has been discussed extensively in current literature and, it is generally considered to play an important role in stabilizing the trunk and pelvis and in transferring force between the lower extremities and the pelvis and trunk.[20,61,64] For example, one study established the relationship between greater gluteal strength and smaller pelvic and trunk movements during athletic movement.[85] Furthermore, decreased hip muscle strength has also been associated with the development of LEI. A systematic review found low to moderate evidence for decreased hip adductor strength as a risk factor for local adductor and groin injuries and,[54] decreased isometric hip external rotation strength was established as a risk factor for general LEI in another study.[64] More recently, a large prospective study investigated the role of different hip muscle strength measures for the development of LEI in which greater bilateral adductor strength was associated with a lower injury risk for any type of knee injury, but was not considered a risk factor after multivariate analysis.[6] Although the possible relationship between isometric hip muscle strength and LEOI has already been described in current literature, this relationship has not yet been investigated prospectively.[79] In **chapter III**, isometric hip muscle strength was measured as described by Thorberg et al.[101] and was prospectively investigated in an active cohort. Hip extension strength, hip external rotation strength and hip extension/flexion strength ratio were all associated with LEOI after univariate analysis, however, only the extension/flexion strength ratio was considered a risk factor after multivariate analysis. A decreased extension/flexion strength ratio was associated with an increased hazard for LEOI and it was hypothesized that the decreased ratio was due to decreased hip extension strength. Decreased strength in hip stabilizing muscles has been associated with LEOI injuries and, a possible injury mechanism for LEI in subjects with decreased hip muscle strength has also been suggested.[36,56,116] A common phenomenon described with decreased hip muscle strength is the occurrence of a greater peak hip adduction angle, greater hip internal rotation and greater frontal plane knee joint moments during movement.[94] Decreased hip extension strength has also been linked to altered running kinematics. For example, isometric hip extension strength has been proven to be significantly correlated with the trunk flexion angle during running, resulting in a more upright trunk position in the presence of decreased hip muscle strength.[100] Furthermore, decreased hip extension muscle strength has been hypothesized to be linked with decreased impact absorption of the lower extremity during functional movement.[27] These findings give further insight into the relationship between decreased hip muscle strength and LEOI and, this might illustrate possible injury mechanisms for these specific injuries.

> Isometric hip muscle and trunk muscle strength was measured with the use of HHD. Trunk flexion strength, hip extension and external rotation strength and hip extension/flexion strength ratio were significantly associated with LEOI. However, only a decreased hip extension/flexion strength ratio could be considered a risk factor for these injuries.

Can core muscle endurance be measured in clinical practice and is it associated with lower extremity injuries?

Endurance capacity of individual muscles or muscle groups can easily be evaluated with the use of isometric holding tests.[9,23,73] These tests are often used since they are easy to perform and require minimal equipment and training for the clinical practitioner.[25] The Biering-Sørensen test, to measure endurance capacity of the trunk extension muscles has been previously confirmed to be a reliable and valid test to measure endurance capacity of the trunk extension muscles. Good to excellent intra- and inter-tester reliability for this test has been described in different studies.[35,58,62,97] Construct validity for this test was investigated by Coorevits et al.[23] sEMG of different trunk extensor muscles and hip muscles was measured during the Biering-Sørensen test and normalized median frequency (NMF) slopes of these EMG signals were analyzed afterwards and validity of the test was confirmed. The side bridging test, as described by McGill et al.,[73] is generally used to measure endurance capacity of lateral core musculature and excellent intra- and inter-tester reliability has been established.[35,57,97] On the other hand, construct validity of this test was only suggested based on perceived fatigue during this test in a study performed by Green et al.[42] Therefore, future research should investigate construct validity based on sEMG and NMF analysis of different hip and trunk muscles during the side bridging test. The prone bridging test was suggested in the general introduction as a functional test to measure endurance capacity of the abdominal core musculature. However, contradicting evidence on reliability for this test is described and validity for this test has not yet been established. Therefore, reliability and construct validity for this test was investigated in **chapter II, part I**. Excellent intra- and inter-tester reliability for this test was found (Table 2) and validity for this test was established after NMF slopes of the EMG signals of different trunk and hip muscles were analyzed.

Table 2 Intra-tester and inter-tester reliability of the prone bridging test

	(ICC 2,1)	95% CI	SEM (s)
Intra-tester reliability	0.89	0.78 – 0.95	20.9
Inter-tester reliability	0.87	0.73 – 0.93	20.75

CI = Confidence Interval; ICC = Intraclass Correlation Coefficient; SEM = Standard Error of Measurement (Seconds)

Reliability and validity to measure endurance capacity of lateral and dorsal core musculature using isometric trunk holding tests has already been established. New evidence supports reliability and validity for the prone bridging test to measure endurance capacity of the ventral core musculature in a healthy population. This test can be used reliably in clinical practice without the use of expensive material.

In **chapter I**, we concluded that the current evidence for core muscle endurance as a risk factor for LEI was inconclusive. Three studies investigated anterior, posterior and lateral core muscle endurance and their relationship with general LEI.[64,108,109] No evidence was found for lateral and posterior core muscle endurance as a risk factor for LEI, and contradictory evidence was found for anterior core muscle endurance as a risk factor for LEI. An update of the current literature did not uncover new evidence for the relationship between core muscle endurance capacities and LEI. Furthermore, to this day there is no evidence which suggests there is an association between core muscle endurance and LEOI.

In **chapter III**, core muscle endurance was prospectively investigated with regards to LEOI. After univariate analysis, the anterior core muscle endurance (as measured with the prone bridging test) and the lateral core muscle endurance on the same side as the injury (as measured with the side bridging test) were significantly associated with LEOI and decreased anterior core muscle endurance capacity was considered as a risk factor for LEOI after multivariate analysis. Research into current literature could give insight into the possible injury mechanisms for LEI in subjects with suboptimal core muscle endurance. In general, it has been suggested that poor endurance of the core muscles negatively affects function throughout the kinetic chain.[21] For example, one study investigated joint kinematics in subjects with fatigued lumbar musculature and found a forward leaning posture and increased joint angle variability at multiple joints distal to the fatigued muscle.[69] These findings are in agreement with other studies that hypothesized low endurance capacity in lumbopelvic musculature to be linked to the inability to avoid excessive hip adduction, knee valgus movement and femoral internal rotation during dynamic tasks.[108,111] Another study found reduced quadriceps muscle activity in subjects with fatigued lumbar musculature in the absence of fatigued quadriceps muscles.[47] This was corroborated by Suter & Lindsay[99] who concluded that subjects with poor trunk muscle endurance had a higher quadriceps muscle inhibition compared to subjects with good muscle endurance capacity, which was attributed to the phenomenon of reciprocal inhibition. Based on these findings, it could be hypothesized that a reduced endurance capacity of the abdominal trunk musculature leads to altered kinematics in distally located joints combined with altered muscle activation patterns during repeated or cyclic movement which could predispose a subject to LEOI. The majority of studies, researching the influence of reduced trunk muscle endurance capacity on biomechanical functioning of trunk and lower extremity, investigate trunk extension muscles rather than trunk musculature in general or abdominal musculature. Therefore, future research should investigate the influence on decreased abdominal muscle endurance and lower extremity kinematics during functional movement.

Core muscle endurance capacity was evaluated with the use of the Biering-Sørensen test, side bridging test and prone bridging test. Significantly lower holding times were found in the injured group for the side bridging test and the prone bridging test. However, only decreased holding time for the prone bridging test was considered a risk factor for LEOI.

Can core sensorimotor control be measured in clinical practice and is it associated with lower extremity injuries?

The need to accurately assess sensorimotor control is widely accepted.[51] However, assessment of sensorimotor control of the core is not as straightforward compared to the assessment of the other core stability components since sensorimotor control itself relies on different musculoskeletal capacities. It relies on afferent proprioceptive input and the following efferent neuromuscular dynamic response for providing and maintaining joint stability.[13,51] Assessment of core neuromuscular control is commonly based on evaluation of muscular activation patterns, quality of movement or control of movement of the trunk and lumbopelvic regions,[106] whereas assessment of core proprioception relies on the evaluation of the repositioning accuracy of the trunk and lumbopelvic regions.[97,115] These aspects are generally evaluated separately and, expensive or self-fabricated lab equipment is oftentimes used for reliable measures of neuromuscular control and proprioception.[82,115] Since the use of such equipment is universally acknowledged to have limited use in clinical practice, there have been studies to suggest clinical assessment methods to evaluate trunk and lumbopelvic neuromuscular control and proprioception. For example, Luomajoki et al.[68] investigated reliability of a self-developed test battery in which subjects needed to perform specific movements in a controlled manner and, lumbopelvic movement control during these tests was evaluated to assess neuromuscular control. They obtained good reproducibility values with the use of a dichotomized score (i.e. correct/ incorrect). It is hypothesized that the use of a dichotomized score results in a loss of information.[45] On the other hand, scoring of a similar test battery with the use of a 7-point scale resulted in low reliability values.[45] Furthermore, validity for such test battery is often not discussed. More recently, a test protocol and scoring method was developed to asses lumbopelvic neuromuscular control for which reliability and validity was established.[32,33] Subjects performed a repeated lumbopelvic movement which was evaluated on five categories: quality of the lumbopelvic motion, control of the adjacent areas, preference of motion direction, breathing, and the amount of good quality repetitions. The five criteria were evaluated afterwards using a rating scale. Concurrent validity was established by comparing the clinical test scores to spinal kinematics. Reliability of the scoring method was investigated a first time and a second time after a short training session for the participants on how to perform the test correctly. Higher agreement values for scoring the test were found for the pre-training performance compared to the post-training performance, suggesting that assessors may have been influenced by an expectation of improved performance after training. Some assessors may have rated performance poorer if they expected greater improvement from training. Therefore, the authors suggested that scoring the test without participant training might be more reliable. As such, this test was implemented in the prospective study of chapter III and will be further described as the **lumbopelvic control test**.

Clinical assessment for core proprioception is based on evaluating repositioning capacities of the trunk and lumbopelvic regions without the use of expensive equipment. For example, Henriksen et al.[49] investigated reliability of inclinometry to evaluate lumbopelvic repositioning capacities in three positions. However, they calculated low ICC values for test-retest reliability, especially for the standing position compared to the sitting position. Based on current literature, there seems to be a lack of clinical tests to measure core proprioception. Therefore, in **chapter II, part III**, reliability of a novel test method (**lumbopelvic position-reposition test**) to assess trunk and lumbopelvic repositioning capacities was discussed. The test performance was based on the protocol of Steven et al.[97] and, a rating scale was used for scoring the test performance. Based on the total test score, good inter-tester and excellent intra-tester reliability was found (Table 3).

Table 3 Intra-tester and inter-tester reliability of the lumbopelvic position-reposition test (ICC values, based on the aggregate test scores, with corresponding SEM values and MDC values)

	ICC (2,1)	95% CI for ICC	SEM*	MDC*
Intra-tester reliability Lumbopelvic position-reposition test	0.87	0.75 – 0.94	0.64	1.76
Inter-tester reliability Lumbopelvic position-reposition test	0.73	0.51 – 0.86	0.85	2.34

CI = confidence interval; ICC = Intraclass Correlation Coefficient; MDC = Minimal Detectable Change; SEM = standard error of measurement. *SEM values and MDC values are represented on a scale from 0-10

Adequate sensorimotor control of the core plays an important role in providing stability during movement and athletic performance.[61] The **SEBT** and the **lateral step down test**, which evaluate dynamic postural stability and quality of movement or control of movement respectively, have been described as a measure for sensorimotor control in a more functional position. The reliable and valid SEBT for postural stability has been suggested as an indicator for core stability since dynamic balance is reliant on core muscle strength, neuromuscular control and proprioception.[20,43,58,83] The SEBT is scored on performance, whereas the lateral step down test is scored on quality of movement and movement control. However, only slight to fair agreement between raters for the latter test (k = 0.19 - 0.22), based on real-time test scoring, have been reported. Therefore, in **chapter II, part III**, reliability for the lateral step down test with video based test scoring, to improve reliability, was investigated. Based on the total test score, excellent intra- and inter-tester reliability was established (Table 4).

Table 4 Intra-tester and inter-tester reliability of the lateral step down test (ICC values, based on the aggregate test scores, with corresponding SEM values and MDC values)

	ICC (2,1)	95% CI for ICC	SEM*	MDC*
Intra-tester reliability Lateral step down test	0.88	0.76 – 0.94	0.44	1.23
Inter-tester reliability Lateral step down test	0.81	0.64 – 0.9	0.51	1.42

CI = confidence interval; ICC = Intraclass Correlation Coefficient; MDC = Minimal Detectable Change; SEM = standard error of measurement. *SEM values and MDC values are represented on a scale from 0-9

New evidence confirms good to excellent reliability for the lumbopelvic position-reposition test to measure core proprioception and excellent reliability for the lateral step down test, a dynamic test to measure core stability. The lateral step down test can be used reliably in clinical practice when using the same test protocol and scoring methods in a healthy population. On the contrary, scoring the lumbopelvic position-reposition test using the novel scoring method is not recommended for use in clinical practice due to low inter-tester agreement on two items.

In **chapter I**, evidence was found for neuromuscular control and proprioception of the core as risk factors for the development of LEI in athletic populations. Decreased repositioning capacity of the trunk was associated with knee injuries and,[115] increased joint displacement of the hip and trunk during functional movement was significantly associated with the development of exertional medial tibial pain.[106] Decreased movement control of the trunk after sudden trunk perturbation was associated with the development of knee injuries and,[114] decreased movement control of the lumbopelvic region while performing specific dynamic tests was associated with general LEI.[89] An update on the current available literature revealed new evidence for impaired neuromuscular control of the core as a risk factor for the development of hamstring injuries.[90,91] Schuermans et al.[90] concluded that the neuromuscular activation pattern of hip and trunk musculature during sprinting was associated with absence from sport due to hamstring injury. Furthermore, the same authors concluded that increased joint movement of trunk and pelvis during swing phase of sprinting increases injury risk for hamstring injuries.[91]

Evidence for core neuromuscular control and proprioception as a risk factor for LEOI remains however limited. As such, these core stability components were prospectively investigated in **chapter III**. Performance on the analytical tests for core neuromuscular control and proprioception (the lumbopelvic control test and the lumbopelvic position-reposition test respectively) were not associated with the development of LEOI. Although decreased repositioning capacity was seen in the injured subjects, this difference was not statistically significant. These results are not in agreement with the aforementioned studies that did find decreased NMC and proprioception in subjects who went on to develop LEI.[113,114]

Furthermore, no significant difference was found for the performance on the lateral step down test between the injured and non-injured group. Although the lateral step down test is widely used to detect neuromuscular control of trunk and lower extremity in patient populations and in healthy subjects,[11,76,86] there are no studies available that use the lateral step down test as an injury screening tool despite the fact that neuromuscular control has already been linked to LEI.[114] Based on the results of our study, the lateral step down test is not suited to identify healthy subjects at risk for LEOI.

On the other hand, after multivariate analysis, an absolute left/right difference for the anterior reach distance on the SEBT was withheld as a risk factor for the development of LEOI. The risk factor associated with the SEBT implies a disparity between the left and right side for postural stability. Based on the results of our study, it seems that a left/right difference in performance of this dynamic test might be more suitable to detect susceptibility for LEOI. Based on current literature and the results of the prospective study, it seems that an anterior reach asymmetry consistently predicts non-contact injuries.[17] Compared to the posterolateral and posteromedial reach directions on the SEBT, it is the anterior reach direction, which closely resembles a unipodal squat, that requires lower extremity strength, neuromuscular control and balance.[39] A side-to-side postural stability difference or imbalance could hypothetically influence overuse injuries in various way, as suggested in previous research.[83] Plisky et al.[83] established that basketball players with an anterior left leg/right leg reach distance difference greater than 4 cm on the SEBT to be 2.5 times more likely to sustain a LEI and hypothesized that imbalance in stability between both legs might alter how a participant reacts to situations in sport activities, causing increased stress to the more capable lower extremity. Second, the more capable lower extremity may absorb excessive force due to instability resulting from poor balance on the less able lower extremity. Finally, the less capable lower extremity may not provide a stable base on which to land or pivot. Although these results are in accordance with the results of our study, more research is needed on the influence of inadequate postural stability on lower extremity biomechanics during movement.

> No measure for core proprioception or core neuromuscular control was significantly associated with LEOI. Based on the outcomes of the dynamic core stability test, an increased left/right asymmetry in the anterior direction on the SEBT was considered a risk factor for LEOI.

The interaction of different core stability components and how it relates to lower extremity overuse injuries

In **chapter III**, we concluded that multiple core stability measures were univariately and significantly associated with the development of LEOI using competing risk analysis, without adjusting for other possible confounders or taking into account the relationship between the different components. However, it is the interaction of deficiencies in different core stability components in the model that is able to identify groups at risk for LEOI. Based on the final multivariate model, the risk factors for the development of LEOI were, an increased left/right asymmetry on the anterior reach direction of the SEBT, a decreased endurance time on the prone bridging test and a decreased isometric hip extension/flexion strength ratio, with gender taken into account as a confounder.

Although other variables were also significantly associated with LEOI, these were not withheld after model building due to multicollinearity. For example, prone bridging holding time was significantly correlated with side bridging holding time ($r = 0.687$) and, hip extension strength was significantly correlated to the hip extension/flexion strength ratio ($r = 0.786$). Furthermore, significant correlations between different attributes within the same muscle groups were found as well, such as abdominal muscle endurance and abdominal muscle strength ($r = 0.4$). Overall, the multitude of correlations found between the different components of core stability suggest an interaction between these components which could reinforce injury risk when impairment in these components is present.

The hypothesis that impairment in one core stability component could be correlated to impairment in other core stability components, reinforcing the risk for injury, has already been demonstrated in earlier research. For example, suboptimal endurance of the core musculature has been associated with impaired sensorimotor control and inhibition of lower extremity musculature.[46,109] Indeed, one study reported reduced trunk repositioning capacities in subjects with fatigued core musculature.[13] Furthermore, since muscle fatigue leads to increased threshold of muscle spindle discharge, it seems that neuromuscular control is compromised for a short period after muscle fatigue, which may lead to a possible inability to dynamically stabilize the joints.[13] Therefore, it can be hypothesized that subjects with decreased endurance capacity experience muscle fatigue more rapidly, which could lead to more distinct deficiencies in sensorimotor control and muscle inhibition. The combination of decreased endurance capacities and decreased hip muscle strength, which itself results in altered movement kinematics, could explain the increased susceptibility for overuse injuries.

Overuse injuries occur with gradual onset over time and are the result of repeated technical movement patterns during sports activities. Reduced endurance capacities of core musculature leads to altered core sensorimotor control and inhibited muscle activation which leads to altered lower extremity kinematics.[46,47] Furthermore, decreased hip extensor muscle strength also leads to altered movement kinematics. As such, we conclude that increased risk for LEOI can be a consequence of the coexistence of deficiencies in different core stability components during prolonged sports activities.

3 Clinical implications

The use of assessment tools in clinical practice

Previous research, executed in laboratory settings, has confirmed that core stability components such as neuromuscular control and muscle strength can be considered as risk factors for LEI.[90,91,106] The authors of these studies indicated the need to translate such results toward clinical practice in the form of easy to administer and cost-effective assessment tools that measure the same construct as measured with laboratory equipment. The studies performed in chapter II attempted to bridge the gap between the measurement of core stability components in a lab setting and the measurement of these components in clinical practice by means of developing novel tests or adjusting existing tests with regards to testing protocol and, by investigating their validity and/or reliability. Five tests were developed and evaluated with regards to standardization and scoring method. The prone bridging test, trunk flexor/extensor strength tests, lumbopelvic position-reposition test and the lateral step down test can all be performed reliably when using the test protocols as described in chapter II. Besides a HHD to measure isometric strength and a basic video camera and a video editing program for analyzing kinematics, no other specialist equipment is needed to perform and score these test. These tests can be used for screening purposes and to keep track of training progression within an injury prevention program as discussed below. Based on the results of the studies in chapter II and chapter III, a proposal could be given for a core stability related test battery to screen for LEOI in a healthy athletic population. The test battery should be developed based on validity/reliability of the tests, feasibility of these tests in clinical practice and the capacity of these tests to accurately classify a subject as being at risk for developing an injury. Therefore, the following tests might be appropriate: Isometric trunk flexion/extension strength tests; isometric hip flexion/extension strength tests; the prone and side bridging test; and the SEBT.

Injury prevention program

The cause for a specific injury event can be described as a condition or characteristic that preceded the event and without which the event would not have occurred.[88] A cause that inevitably produces an event (the injury) is described as sufficient. In order to be sufficient, the cause for injuries to develop is made up of different risk factors.[88] Prospective cohort studies attempt to identify risk factors associated with a specific type of injury. As such, these studies are aimed at explaining an injury by identifying the cause and are a critical aspect for injury prevention.[74,88] Using the evidence found in these studies, the following step in the process of injury prevention is the introduction of injury prevention programs implementing preventive measures that are likely to reduce future risk and/or severity of injuries.[74,104] The efficacy of such prevention programs has already been confirmed through the implementation of prevention programs, able to drastically reduce the incidence musculoskeletal injuries.[14,92,93] For example, a randomized control trial investigating the effect of an injury prevention program in professional football players, including exercises to improve core muscle strength and dynamic balance has already established a significant decrease in general musculoskeletal injury rate by 46.1% in the intervention group.[92]

As such, the implementation of core stability exercises in an injury prevention program is warranted and might provide a successful addition toward primary prevention of LEOI in a healthy athletic population.

Taking into account the results found in the prospective study in chapter III and general training principles, the set-up of the injury prevention program should consider the following basics:

- In general, training and normalization of potential contributors to injury (eg. impaired core stability components) should not be the sole focus of a training program aimed at preventing LEOI in a healthy population.[28] It is rather an relevant contribution within an injury prevention program.

In an ideal situation, the performed core stability exercises should be implemented within a comprehensive and multifaceted prevention or rehabilitation protocol, aimed at training the entire kinetic chain in line with the sport specific needs with regard to endurance, strength, sensorimotor control, flexibility, speed and explosivity among others.[55,98] Furthermore, general aspects such as awareness education on injury mechanisms and, adequate warm-up needs to be included as well.[40]

- The core stability aspect of the prevention program should commence with exercises that isolate specific core muscles groups in order to normalize impairments.[52] The exercises given at the start can be low threshold core stability exercises which incorporate training of separate impaired core stability components in order to familiarize subjects with specific exercises and training principles.
- These basic exercises need to progress towards exercises that include the activation of the same muscle groups within more complex 3D movements in accordance to a specific sport and need to target different impaired core stability components at once.[1,55]
- With any given exercise, it is imperative for the coach, physical trainer or therapist to supervise that the exercises are performed with a spinal position as neutral as possible (dependent on which specific exercise) and with optimal engagement of deep and superficial core stability musculature.[55] Specifically, any cues that cause hollowing of the abdominal wall, which compromises the function of the more superficial muscles that embrace the trunk, should be avoided.[72]
- As with any form of training, a varied exercise selection, periodization, the overload principle and systematic progression must be evaluated periodically in order to assess efficiency of the given training program and its intended goal.[15,67] Systematic progression can be achieved by adjusting the frequency, intensity, the duration and volume of the training bout.[53]

Providing a comprehensive injury prevention program is not within the scope of this dissertation. However, some examples of exercises commonly used in fitness and rehabilitation will be described below. Various exercises will be provided accompanied with progression possibilities. In accordance with the results of the prospective study, these exercises are primarily aimed at normalizing left/right postural stability asymmetry, hip extension/flexion strength ratio and, are aimed at improving abdominal core muscle endurance.

Please note that this is not an exhaustive list of exercises and, given the specific nature of different sports, there will be no focus on sport specific exercises but rather general exercises. Furthermore, this dissertation does not aim to focus on the basic principles of core stability training which teach a subject to perceive neutral spine curvature and core muscular activation in different positions on the one hand and controlled lumbopelvic movement on the other hand.

(1) The prone bridging test is a reliable test to evaluate muscle endurance.[25] It also provides an adequate stimulus for training core muscle endurance when holding this position for an extended period of time.[31] It can be used as a low threshold exercise for training and optimizing core muscle endurance in general (Figure 1A) and, variations on this exercise are easily added. The prone hip extension (Figure 1B), using a resistance band, can be applied to train hip extension strength combined with core muscle endurance. Gluteus maximus activity during this exercise has even been shown to be as high as 75% of the MVIC.[12] An added hip abduction during hip extension in this exercise results in even higher gluteus maximus activity and adds a trunk rotational component to the exercsie.[59] The prone running exercise (Figure 1C) can be used to add explosivity for sprint related sports and, the prone 'spiderman' (or prone oblique knee raise) (Figure 1D) exercise can be performed to add trunk rotational strength training and hip external rotation strength training and all exercises can be complemented with the use of a resistance band.

(2) Romanian deadlifts (sometimes referred to as stiff legged deadlifts) (Figure 2A) are an excellent exercise to elicit greater hip extensor muscle activity compared to hip flexor muscle activity.[71] Therefore, this exercise can be implemented to normalize hip extension/flexion strength ratio in the presence of weak hip extensor musculature. Research has also established a greater gluteus maximus activity compared to other hip musculature activity during single leg variations of the Romanian deadlift (Figure 2B).[29] Furthermore, when performing these single leg variations, single leg balance will be trained as well. Extra material, such as resistance bands, free weights or unstable surfaces, can be used in order to build in progression within these exercises. A more dynamic variation on the Romanian deadlift is the kettlebell swing (Figure 2C). A recent study measured EMG activity and 2D kinematics during a kettlebell swing and the results supported the clinical value and the use of the kettlebell swing exercises to address clinical strength and endurance impairments specific to the gluteal, hamstring and trunk musculature.[103] In order to add a rotational component to the exercise, it can also be performed one-handed.

(3) Contrary to the single leg deadlift variations, split squat exercises, such as the Bulgarian split squat (with the rear foot elevated, Figure 3A) involve activity of both legs and have been widely used to enhance jumping, sprinting and agility performance.[95] As high as 85% of the external load during performance of this exercise is supported by the front, as reported by McCurdy et al.[70] Compared to a standard squat exercise, the split squat has been established as a more hip dominant exercise eliciting more hip extensor muscle (hamstrings and gluteus maximus) activity compared to quadriceps activity.[2,70,71] Furthermore, more

abdominal muscle activity was found during a split squat exercise compared to a standard squat exercise with equal load.[2] These results suggest that performing a split squat might be able to train trunk muscle strength concurrently with hip muscle strength normalization. On the other hand, it should be noted that trying to improve balance by solely performing split squat exercises might not be favorable since no correlation could be established between split squat strength and unipodal balance capacities.[70] Different variations on this exercise are possible, such as the regular split squat (both feet on the ground, Figure 3B), which allows for greater movement freedom and assistance from the rear leg. More dynamic variations can be performed as well, such as the forward lunge exercise. As possible progression, all of the aforementioned exercises can be combined with catching and throwing activities of the upper limb to add trunk rotational muscle activity and stability training (Figure 3C, forward lunges combined with catching and throwing).

(4) Other exercises which could be included at the injury prevention program targeted at normalizing and optimizing core muscle strength and endurance in accordance with the results of the prospective study are single leg squat variations, supine glute bridge variations, good mornings, Nordic hamstrings and glute-ham raises, amongst others.

Some considerations and future guidelines with regards to injury prevention programs are in place. Randomized controlled trials under ideal conditions can be seen as the gold standard to truly evaluate the efficacy of an intervention aimed at injury prevention and, they are the next logical step towards effective injury prevention implementation.[104,105] To assess the efficiency of a preventative measure, the economic consequences, the impact on performance and the decrease in injury risk need to be considered and, in order to effectively perform injury prevention for LEOI, these programs must take place in a daily sporting center and/or clinical environment under everyday circumstances.[104] A final general consideration is the need for injury prevention research to deliver a final product which implements a relevant action plan based on procedures for clubs or professional organizations to adopt. Moreover, it might also be considered to extend the intervention plan more broadly to other sports, or sports injury problems.

Considerations for injury screening and injury prediction

In general, the findings of our prospective study suggests that impaired components of core stability take part in the cause for LEOI. In order to train and normalize the impaired parameters to reduce injury risk, low risk and high risk subjects can be identified with a predictive accuracy of 53%, a sensitivity of 87.9% and a specificity of 42.2%, based on the model presented in chapter III. These results suggest that the subjects which are truly at risk for developing an injury can be identified

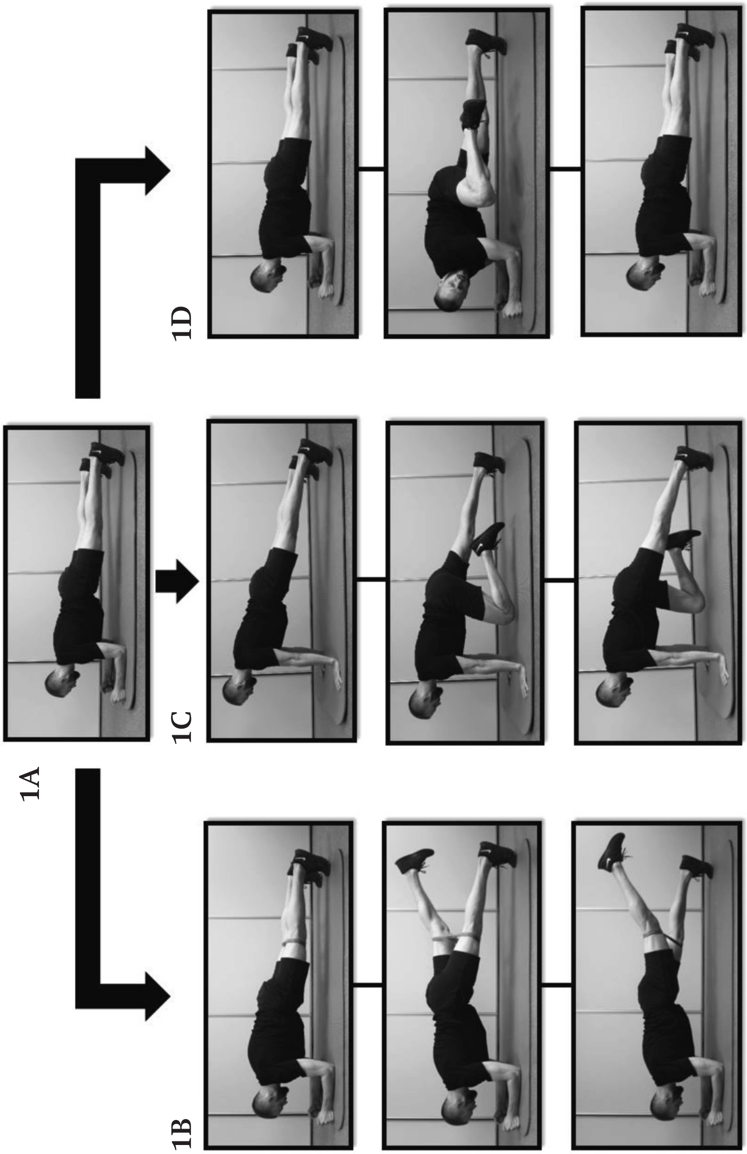


Figure 1A-D Prone bridging exercise for core muscle endurance and possible progression

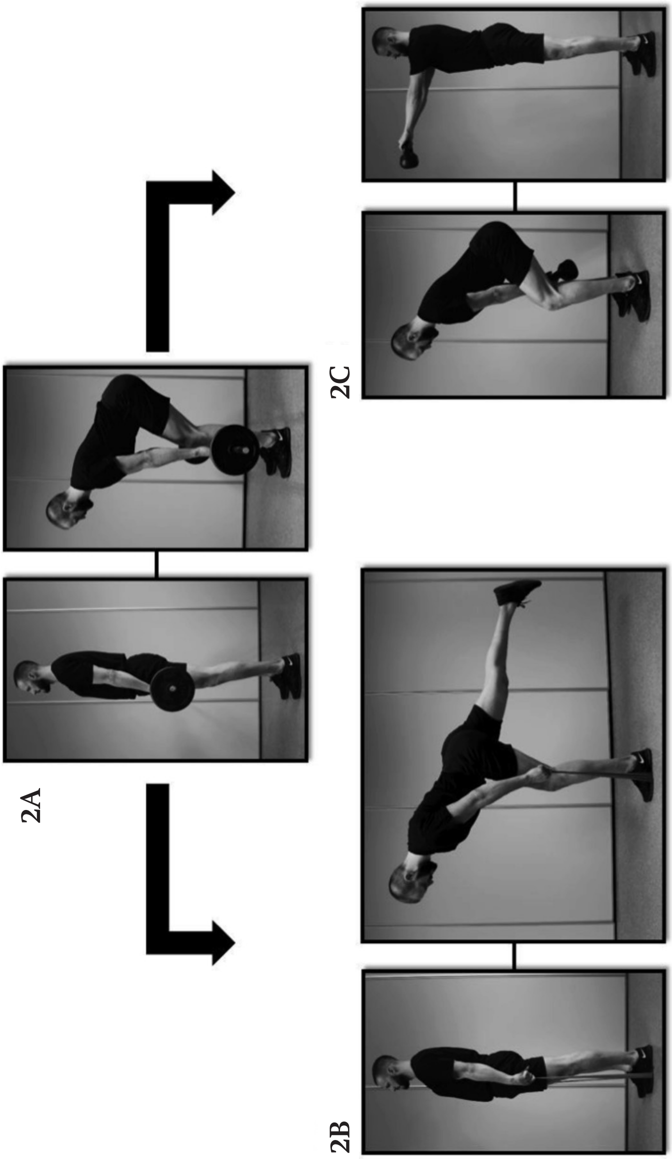


Figure 2A-C Romanian deadlift exercise for hip extension strength and possible variations

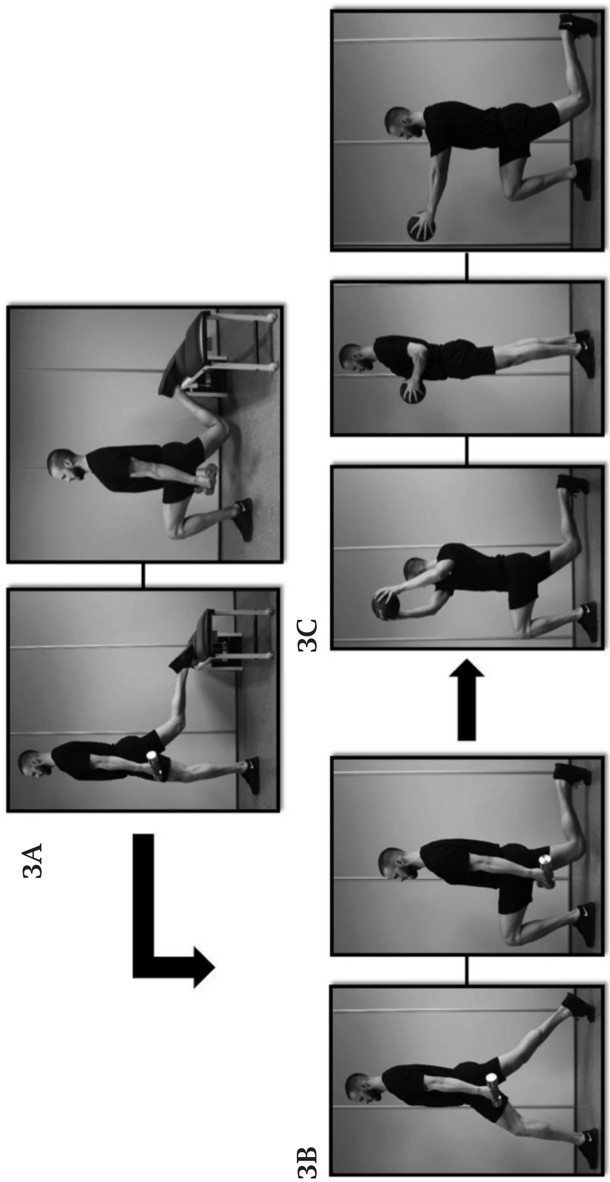


Figure 3A-C Bulgarian split squat and possible dynamic variations reliably due to the high sensitivity. Due to calculation of a cut-off value for this specific model, it is possible to identify groups with high prognostic scores for overuse injuries and groups with low prognostic scores. However, the use of cut-off values for determining subjects at risk has been criticized. Cook[22] declares that although dividing quantitative values (transforming the data) into categories improves the interpretability of the clinical finding but desensitizes the data and, as with small sample sizes, can fail to identify patterns. It is better to consider the current predictors as dimensions (rather than a tool with a dedicated and discriminative value) that reflect a construct that is needed within a given sport.[22]

Furthermore, it should be noted that predicting risk for injury for an individual, based on injury screening, needs to be done with caution. The purpose of injury screening and prediction is indeed to identify risk factors present in individuals, allowing for targeted intervention in order to prevent injury. However, the significant group findings (the associations between the risk factors and the injury) might not be directly translated as individual risk. The mean risk for a group indicates the proportion of individuals for whom risk factors are present and can be considered explanatory whereas the actual risk for the individual is a matter of whether or not a risk factor will lead to injury, which can be considered as predictive.[88]

4 Strengths and limitations

In retrospect of the performed research as described in chapter I, II and III, the various strengths of the of this dissertation should be highlighted. This is the first study to evaluate all different components, which contribute to stability of the core, within one cohort. Furthermore, all the different components were evaluated within a multisport athletic population. Oftentimes only one specific component of core stability is investigated while still reporting on core stability as a whole.[26] Bringing together the different tests to evaluate core stability components allowed for the investigation of how these components interact with each other in the injury prone subjects through multivariate analysis. Results of the prospective study do highlight the importance of this interaction on the development of injuries. Furthermore, the authors attempted to bring together reliable and valid tests which are easy to use in clinical practice. These tests are generally not time-consuming and do not require the use of expensive material. As such, the results of current dissertation can be implemented in clinical practice to detect athletic subjects at risk for LEOI. This is the first study to implement the valid and reliable lumbopelvic control test and the recently developed, reliable lumbopelvic position-reposition test. Both these tests provide a more analytical, easy to perform alternative to more dynamic and functional tests, which purportedly measure sensorimotor control, in which interference of other musculoskeletal capacities could play a role.

In order to determine a causative relationship between measured variables and the outcome of interest, studies need to utilize a longitudinal study design.[81] Competing risk analysis, as described by Fine and Gray,[37] was used in the prospective study to investigate the association between core stability and injury and can be seen as an extension on the cause-specific Cox proportional hazards model by considering the subdistribution hazard. The subdistribution hazard re-establishes a one-to-one relationship and consequently offers a summarizing analysis of separate cause-specific hazards analyses.[8] Contrary to cause-specific analyses, in which competing events are censored, the Fine and Gray analysis introduces the competing events in the risk set, with appropriate weighting, and does not censor them.[38] In addition, the use of a multilevel injury registration method, in which a weekly online registration was combined with a three-monthly retrospective interview, was a strength within the study design. The use of a weekly online questionnaire in registering overuse injuries has been proven beneficial. Clarsen et al.[19] compared overuse injuries in elite athletes that were reported to the coach or physical therapist during training sessions versus those injuries that were reported using a weekly email questionnaire. They found that the email questionnaire captured 10-fold more overuse injuries. Furthermore, it has been suggested that diagnostic accuracy likely improves in injuries which are documented by an on-site physician, while injuries for which medical attention is not sought are likely to be missed.[65] These findings argue for expanding overuse injury registration methods to include a method of self-reporting, so that the injuries analyzed are not limited to only those that reach the attention of an athletic trainer or team physician.[80]

Next to the strengths, some methodological considerations and limitations need to be taken into account as well when interpreting these results..

In **chapter II**, validity and/or reliability of different tests was investigated in order to complement other validated, reliable tests to measure different components of core stability. When considering the tests altogether, discussion could arise on whether or not these tests are functional enough to examine core stability and how it functions during movement. Since core stability is important in providing a stable base on which efficient and safe movement can be built upon, it has been suggested that assessment of core stability should also be dynamic, and should include tests that evaluate specific functions and directions of three planar movement.[61,110] Quantifying core stability in a dynamic situation has previously been performed with the use of 3D movement analysis or sEMG analysis.[90,91,106] However, determining validity and reliability of sport specific, dynamic tests that measure trunk or lumbopelvic kinematics without the use of laboratory equipment seems a challenging task, given that such tests are prone to a substantial amount of within-individual variability.[107] Furthermore, evaluation of dynamic tests implies quantification of the amount of lumbopelvic or trunk excursion during movement, however, they do not allow to infer on how different components such of core stability such as strength or endurance influence these movement patterns.

No specific test has been incorporated to specifically measure isometric trunk rotation and lateral flexion strength, although these functions are important for contributing to core stability.[61] However, performing isometric trunk flexion also solicits force production of the internal/external oblique muscles, which are the prime movers for trunk rotation and, co-contraction with the rectus abdominis occurs.[41] As such, the isometric trunk flexion strength can be considered as a strength test to evaluate the muscle groups responsible for trunk rotation.

It should be noted that lumbopelvic control test and the lumbopelvic position-reposition test, as originally described by Elgueta-Cancino et al.[32] and Stevens et al.[97] were originally developed to detect neuromuscular and proprioceptive deficits in low back pain patients. Therefore, the established discriminant validity to differentiate between good and bad performers is only applicable within a low back pain group. Further research to differentiate good and bad performers in a healthy population is needed. Furthermore, both these tests have only evaluated trunk and lumbopelvic neuromuscular control and proprioception in the sagittal plane. Future research should try to incorporate evaluation in the frontal and transverse plane to gain full insight into these core stability components. It should also be noted that validity was not established for every included test. Validity on the lateral step down test and the lumbopelvic position-reposition test was not investigated. Therefore, future research should consider validating these tests which will be discussed more in detail in the 'Future perspectives' section.

In **chapter III**, a prospective study was executed. No formal sample size calculations were performed to determine whether the prospective study had adequate power. Following the methodological considerations set out by Bahr and Holme,[5] 30 to 40 injury cases would be needed to detect strong to moderate associations, while it is suggested that 200 injury cases are needed to detect small to moderate associations. Therefore, it is possible that only strong associations were identified in our study. However, it should be noted that these numbers are based on calculations for a Cox regression model, without adjusting for other factors, and that the uninjured players will be on average exposed to the sport of football during 90% of the season.[5] Due to a relatively small cohort in our study and/or proportion of injury cases, it is also possible that interpreting negative findings in our study could lead to a type 2 error (overlooking a true effect).

Across the performed studies within this dissertation, specific study populations were recruited with regards to age and sports participation. In order to justify the use of the novel core stability tests (chapter II) in the prospective study of chapter

III, similar populations were needed to ascertain validity and/or reliability of these tests. Young athletic participants were used in these studies which limits possible generalization of results and conclusion towards other populations. Therefore it needs to be considered that the outcome measures of the different novel core stability tests, for which validity and/or reliability was examined in the current dissertation, can indeed only be regarded as reliable for these particular purposes for this particular type of subjects. Certain characteristics of these tests would make it difficult to achieve consistent results with other types of subjects.

Finally, recent studies suggest that a single periodic health evaluation at the start of the research might not be sufficient to analyze risk factors and develop predictive models since the measured variables might alter during the season.[6,102] Variability might occur as a result of changes in response to training, workload, familiarization with the test procedure amongst others. Since measurement of these factors was outside of the scope of the prospective study, we did not take into account these different factors in our analyses. Re-screening of the different variables at a more frequent rate has been suggested as such.[48] Minimal detectable changes should be considered when investigating variability between test moments and variability should be taken into account in the risk factor analysis.

5 Future perspectives

Several research questions were answered by conducting the separate studies of the present dissertation, which contributed to the current evidence. However, some study results raise new questions for which future research is warranted. The results from the different chapters will be discussed and recommendations will be given on how these results could be utilized for research in the near future. Furthermore, a more general outlook on how research into injury screening and injury prevention could/should evolve will be discussed shortly within the scope of this dissertation.

In **chapter II**, the aim was to establish validity and/or reliability for clinical measurement tools. All investigated tools were proven to be reliable and valid with the exception of the lumbopelvic position-reposition test and the lateral step down test, two tests for which validity was not verified. Concurrent validity of both these tests can be examined when compared to 3D movement analysis. In both tests, different items are evaluated for which the amount of repositioning capacity or the amount of movement pattern deviation is subjectively assessed by the rater and can be compared to range of movement as measured with 3D. Furthermore, due to due to low inter-tester agreement on two items for the lumbopelvic position-reposition test, the scoring method should be revisited in future research. For this dissertation, the tests for core stability was performed by physical education students, a cohort of subjects not focusing on one specific sport. Although the importance to assess the generic qualities underlying core stability has been stated, it has been suggested that sports-related testing protocols might be appropriate to test high-level athletes since it has been proven that depending on the sport, athletes display a different aptitude for achieving core stability.[7] Therefore, developing a sport specific test protocol, based on nonspecific tests, might be useful when working with high-level athletes.

Positive results for risk factor identification within a lab setting solicit the extrapolation of these results towards clinical practice.[91,106] It has been previously suggested there is a need to find parallels and correlations between laboratory investigation methods and more easy to administer, less time- and money consuming assessment tools, examining similar outcome parameters. In the current dissertation, an attempt has been made to implement and adapt such assessment tools. However, a gap still exists between real life situational testing in laboratory settings and field test settings. Due to technological advancements there might be a solution for these issues. For example, wearable sensors are an ever evolving technology and is increasingly popular in different sports.[112] An example of wearable sensor technology is an IMU (Inertial Measurement Unit) which is equipped with an accelerometer, gyroscope and sometimes magnetometer and can be easily fabricated into sports garments.[16,66] These apparatuses are able to register different spatiotemporal parameters and as such should be able to measure dynamic joint stability. These tools might be able to replace expensive, not commercially available equipment and can still be used in dynamic situations to quantify core stability. Furthermore, prospective research often only considers time as exposure, and not the amount of workload or measures related to workload. Since this could play an important role in LEOI, there is need for future research to take into account workload. The use of innovative wearable sensor technology might partially cater to this need.

The study in **chapter III** is the first study to prospectively measure the different components of core stability within a cohort at actual risk of injury. Therefore, additional research is necessary in order to further investigate and confirm the present findings. Throughout the discussion it was suggested that impaired core stability was linked to altered trunk and lower extremity kinematics. In order to gain more insight into the relationship between these measurements and LEOI on the one hand, and into the injury mechanism of LEOI on the other hand, future research should be conducted to see if impaired muscle strength, or abdominal muscle endurance can be associated with altered trunk or lower extremity kinematics. Furthermore, it would be beneficial to extrapolate these findings to more specific sports in which LEOI have a high prevalence and these findings should be translated into specific rehabilitation and prevention strategies to find out if adjustments in the impaired components (through training) effectively have the capacity to reduce the risk for LEOI, and how adjustments should ideally be implemented (types of exercises, frequency, volume, intensity and the implementation within training or competition schedules).

Although the current methods for determining risk factors are used in sports medicine and results of studies using these methods are being successfully implemented in clinical practice, there have been suggestions for future risk factor identification studies. The current models, even multivariate models accounting for exposure, are suggested to include predictors that are described as too refined and restrictive to replicate real world situations.[22] Therefore, the suggested next step for risk factor identification studies is the implementation of 'dynamic complex systems', a system in which different individual predictors interact to form an emergent behavior (such as an injury).[22,84] To this day there is lack of knowledge on how different predictors, which are identified using current models, might be altered or interact with each other in a dynamic system in the context of musculoskeletal injuries. Therefore a complex systems approach has been suggested to better reflect the dynamic nature of sports injuries.[10] This approach requires the application of appropriate predictive modelling for investigations of interactions between different risk factors, and how these interactions might influence, or even alter each other to form different patterns of injury risk in order to reflect a more real-world situation.

6 General conclusion

Despite the widespread use of core stability and core stability training in the area of rehabilitation, injury prevention and athletic training, ambiguity still surrounds this concept. An attempt was made throughout this dissertation to deliver new evidence and give more insight into the concept of core stability with regards to what is already known in current literature, how it can be evaluated and how impaired core stability relates to the development of lower extremity injuries.

First, a systematic review of the current literature revealed that

- to this day there is still no uniform definition to describe core stability and different methods and techniques are used to evaluate or quantify stability of the core.
- there is evidence to support the hypothesis that impaired core stability can be considered a risk factor for musculoskeletal lower extremity injuries.
- different components that contribute to stabilizing the core, such as muscle strength and neuromuscular control, were associated with lower extremity

injuries. However, the evidence was limited and conflicting for some components and only one study investigated the influence of core stability on overuse injuries, emphasizing the need for more high quality research.

Second, validity and/or reliability of novel tests to evaluate different core stability components in a healthy population was investigated. Results confirm that

- the valid prone bridging test to assess abdominal muscle endurance can be performed reliably in clinical practice.
- isometric trunk flexor and trunk extensor strength measurements with a handheld dynamometer are reliable and are considered valid when compared to a stable dynamometer.
- proprioception of the trunk and lumbopelvic region can be evaluated based on repositioning capacities in a reliable manner when using the total score for video based test scoring, but it is not suggested to be used in clinical practice due to low agreement inter-tester agreement on two separate test items.
- scoring the lateral step down test to dynamically measure neuromuscular control of the trunk pelvis and lower extremity is reliable when using video based test scoring.

Finally, a prospective study was performed in which an athletic population performed the different core stability tests in order to investigate whether or not impaired core stability could be associated with lower extremity overuse injuries. This study revealed that

- a left/right asymmetry in postural balance combined with decreased endurance capacity of the abdominal musculature and a decreased isometric hip extension/ flexion strength ratio can be considered as risk factors for the development of lower extremity overuse injuries.

In conclusion, a successful attempt was made to gain more insight into core stability and, the studies presented within this dissertation provide newfound knowledge on this concept. However, more research is still needed in order to fully understand its role in the development of lower extremity overuse injuries and how it can be used for injury prevention.

References

1. Akuthota V, Ferreiro A, Moore T, Fredericson M. Core stability exercise principles. *Curr Sports Med Rep*. 2008;7(1):39-44.
2. Andersen V, Fimland MS, Brennset O, et al. Muscle activation and strength in squat and Bulgarian squat on stable and unstable surface. *Int J Sports Med*. 2014;35(14):1196-1202.
3. Anderson K, Behm DG. The impact of instability resistance training on balance and stability. *Sport Med*. 2005;35(1):43-53.
4. Arnold CM, Warkentin KD, Chilibeck PD, Magnus CRA. The reliability and validity of handheld dynamometry for the measurement of lower-extremity muscle strength in older adults. *J Strength Cond Res*. 2010;24(3):815-824.
5. Bahr R, Holme I. Risk factors for sports injuries-a methodological approach. *Br J Sports Med*. 2003; 37(5):384-392.
6. Bakken A, Targett S, Bere T, et al. Interseason variability of a functional movement test, the 9+ screening battery, in professional male football players. *Br J Sports Med*. 2017;51(14):1081-1086.
7. Barbado D, Barbado LC, Elvira JLL, van Dieën JH, Vera-Garcia FJ. Sports-related testing protocols are required to reveal trunk stability adaptations in high-level athletes. *Gait Posture*. 2016;49:90-96.
8. Beyersmann J, Schumacher M. Time-dependent covariates in the proportional subdistribution hazards model for competing risks. *Biostatistics*. 2008;9(4):765-776.
9. Biering-Sørensen F. Physical measurements as risk indicators for low-back trouble over a one-year period. *Spine (Phila Pa 1976)*. 1984;9(2):106-119.
10. Bittencourt NFN, Meeuwisse WH, Mendonça LD, Nettel-Aguirre A, Ocarino JM, Fonseca ST. Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition-narrative review and new concept. *Br J Sports Med*. 2016;50(21):1309-1314.
11. Bolt D, Giger R, Wirth S, Swanenburg J. Step-down test assessment of postural stability in Patients with chronic ankle instability. *J Sport Rehabil*. 2018;27(1).
12. Boren K, Conrey C, Le Coguic J, Paprocki L, Voight M, Robinson TK. Electromyographic analysis of gluteus medius and gluteus maximus during rehabilitation exercises. *Int J Sports Phys Ther*. 2011;6(3):206-223.
13. Boucher JA, Abboud J, Descarreaux M. The influence of acute back muscle fatigue and fatigue recovery on trunk sensorimotor control. *J Manipulative Physiol Ther*. 2012;35(9):662-668.
14. Brukner P. Hamstring injuries: prevention and treatment-an update. *Br J Sports Med*. 2015;49(19): 1241-1244.
15. Buford TW, Rossi SJ, Smith DB, Warren AJ. A comparison of periodization models during nine weeks with equated volume and intensity for strength. *J strength Cond Res*. 2007;21(4):1245-1250.
16. Chambers R, Gabbett TJ, Cole MH, Beard A. The use of wearable microsensors to quantify sport-specific movements. *Sports Med*. 2015;45(7):1065-1081.
17. Chimera NJ, Warren M. Use of clinical movement screening tests to predict injury in sport. *World J Orthop*. 2016;7(4):202-217.
18. Cholewicki J, McGill SM. Mechanical stability of the in vivo lumbar spine: Implications for injury and chronic low back pain. *Clin Biomech*. 1996;11(1):1-15.
19. Clarsen B, Myklebust G, Bahr R. Development and validation of a new method for the registration of overuse injuries in sports injury epidemiology: the Oslo Sports Trauma Research Centre (OSTRC) overuse injury questionnaire. *Br J Sports Med*. 2013;47(8):495-502.
20. Colston MA. Core stability, part 1: Overview of the concept. *Int J Athl Ther Train*. 2012;17(1):8-13.
21. Colston MA. Core stability, part 2: The core-extremity link. *Int J Athl Ther Train*. 2012;17(2):10-15.
22. Cook C. Predicting future physical injury in sports: It's a complicated dynamic system. *Br J Sports Med*. 2016;50(22):1356-1357.
23. Coorevits P, Danneels L, Cambier D, Ramon H, Vanderstraeten G. Assessment of the validity of the Biering-Sørensen test for measuring back muscle fatigue based on EMG median frequency characteristics of back and hip muscles. *J Electromyogr Kinesiol*. 2008;18(6):997-1005.
24. Cuthbert SC, Goodheart GJ. On the reliability and validity of manual muscle testing: a literature review. *Chiropr Osteopat*. 2007;15(1):4.

25. De Blaiser C, De Ridder R, Willems T, et al. Evaluating abdominal core muscle fatigue: Assessment of the validity and reliability of the prone bridging test. *Scand J Med Sci Sport*. 2018;28(2):391-399.
26. De Blaiser C, Roosen P, Willems T, Danneels L, Vanden Bossche L, De Ridder R. Is core stability a risk factor for lower extremity injuries in an athletic population? A systematic review. *Phys Ther Sport*. 2018;30:48-56.
27. De Ridder R, Witvrouw E, Dolphens M, Roosen P, Van Ginckel A. Hip strength as an intrinsic risk factor for lateral ankle sprains in youth soccer players: A 3-season prospective study. *Am J Sports Med*. 2017;45(2):410-416.
28. DiFiori JP, Benjamin HJ, Brenner JS, et al. Overuse injuries and burnout in youth sports: A position statement from the American Medical Society for Sports Medicine. *Br J Sports Med*. 2014;48(4):287-288.
29. Distefano LJ, Blackburn JT, Marshall SW, Padua DA. Gluteal Muscle Activation During Common Therapeutic Exercises. *J Orthop Sport Phys Ther*. 2009;39(7):532-540.
30. Ebenbichler GR, Oddsson LIE, Kollmitzer J, Erim Z. Sensory-motor control of the lower back: Implications for rehabilitation. *Med Sci Sports Exerc*. 2001;33(11):1889-1898.
31. Ekstrom RA, Donatelli RA, Carp KC. Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. *J Orthop Sports Phys Ther*. 2007;37(12):754-762.
32. Elgueta-Cancino E, Schabrun S, Danneels L, Hodges P. A clinical test of lumbopelvic control: Development and reliability of a clinical test of dissociation of lumbopelvic and thoracolumbar motion. *Man Ther*. 2014;19(5):418-424.
33. Elgueta-Cancino E, Schabrun S, Danneels L, van den Hoorn W, Hodges P. Validation of a clinical test of thoracolumbar dissociation in chronic low back pain. *J Orthop Sport Phys Ther*. 2015;45(9):703-712.
34. Emery CA, Maitland ME, Meeuwisse WH. Test-retest reliabilty of isokinetic hip adductor and flexor muscle strength. *Clin J Sport Med*. 1999;9(2):79-85.
35. Evans K, Refshauge KM, Adams R. Trunk muscle endurance tests: Reliability, and gender differences in athletes. *J Sci Med Sport*. 2007;10(6):447-455.
36. Ferber R, Hreljac A, Kendall KD. Suspected mechanisms in the cause of overuse running injuries: A clinical review. *Sport Heal A Multidiscip Approach*. 2009;1(3):242-246.
37. Fine JP, Gray RJ. A proportional hazards model for the subdistribution of a competing risk. *J Am Stat Assoc*. 1999;94(446):496.
38. Forsblom C, Harjutsalo V, Thorn LM, et al. Competing-risk analysis of ESRD and death among patients with type 1 diabetes and macroalbuminuria. *J Am Soc Nephrol*. 2011;22(3):537-544.
39. Garrison JC, Bothwell JM, Wolf G, Aryal S, Thigpen CA. Y-balance test™ anterior reach symmetry at three months is related to single leg functional performance at time of return to sports following anterior cruciate ligament reconstruction. *Int J Sports Phys Ther*. 2015;10(5):602-611.
40. Goossens L, De Ridder R, Cardon G, Witvrouw E, Verrelst R, De Clercq D. Injury prevention in physical education teacher education students: lessons from sports. A systematic review. *Eur Phys Educ Rev*. June 2017:1356336X1771167.
41. Granata KP, Lee PE, Franklin TC. Co-contraction recruitment and spinal loading during isometric trunk flexion and extension. *Clin Biomech*. 2006;20(10):1029-1037.
42. Greene PF, Durall CJ, Kernozek TW. Intersession reliability and concurrent validity of isometric endurance tests for the lateral trunk muscles. *J Sport Rehabil*. 2012;21(2):161-166.
43. Gribble P, Hertel J. Considerations for normalizing measures of the star excursion balance test. *Meas Phys Educ Exerc Sci*. 2009;7(2):37-41.
44. Guilhem G, Giroux C, Couturier A, Maffiuletti NA. Validity of trunk extensor and flexor torque measurements using isokinetic dynamometry. *J Electromyogr Kinesiol*. 2014;24(6):986-993.
45. Habets B, van Cingel REH, Ostelo RWJG. Reproducibility of a battery of commonly used clinical tests to evaluate lumbopelvic motor control. *Phys Ther Sport*. 2015;16(4):331-339.
46. Hammill RR, Beazell JR, Hart JM. Neuromuscular consequences of low back pain and core dysfunction. *Clin Sports Med*. 2008;27(3):449-462.
47. Hart JM, Fritz JM, Kerrigan DC, Saliba EN, Gansneder BM, Ingersoll CD. Reduced quadriceps activation after lumbar paraspinal fatiguing exercise. *J Athl Train*. 2006;41(1):79-86.
48. Hayen A, Dennis RJ, Finch CF. Determining the intra- and inter-observer reliability of screening tools used in sports injury research. *J Sci Med Sport*. 2007;10(4):201-210.

49. Henriksen M, Lund H, Bliddal H, Danneskiold-Samsøe B. Dynamic control of the lumbopelvic complex; lack of reliability of established test procedures. *Eur Spine J*. 2007;16(6):733-740.
50. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492-501.
51. Hewett TE, Paterno M V, Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop Relat Res*. 2002;(402):76-94.
52. Hibbs AE, Thompson KG, French D, Wrigley A, Spears I. Optimizing performance by improving core stability and core strength. *Sport Med*. 2008;38(12):995-1008.
53. Hoover DL, VanWye WR, Judge LW. Periodization and physical therapy: Bridging the gap between training and rehabilitation. *Phys Ther Sport*. 2016;18:1-20.
54. Hrysomallis C. Hip adductors strength, flexibility, and injury risk. *J Strength Cond Res*. 2009;23(5): 1514-1517.
55. Huxel Bliven KC, Anderson BE. Core Stability Training for Injury Prevention. *Sports Health*. 2013;5(6): 514-522.
56. Ireland ML, Willson JD, Ballantyne BT, Davis IM. Hip strength in females with and without patellofemoral pain. *J Orthop Sport Phys Ther*. 2003;33(11):671-676.
57. Ito T, Shirado O, Suzuki H, Takahashi M, Kaneda K, Strax TE. Lumbar trunk muscle endurance testing: An inexpensive alternative to a machine for evaluation. *Arch Phys Med Rehabil*. 1996;77(1):75-79.
58. Kahraman BO, Sengul YS, Kahraman T, Kalemci O. Developing a reliable core stability assessment battery for patients with nonspecific low back pain. *Spine (Phila Pa 1976)*. 2016;41(14):E844-E850.
59. Kang S-Y, Jeon H-S, Kwon O, Cynn H-S, Choi B. Activation of the gluteus maximus and hamstring muscles during prone hip extension with knee flexion in three hip abduction positions. *Man Ther*. 2013;18(4):303-307.
60. Karata GK, Gögü F, Meray J. Reliability of isokinetic trunk muscle strength measurement. *Am J Phys Med Rehabil*. 2002;81(2):79-85.
61. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med*. 2006;36(3):189-198.
62. Latimer J, Maher CG, Refshauge K, Colaco I. The reliability and validity of the Biering-Sorensen test in asymptomatic subjects and subjects reporting current or previous nonspecific low back pain. *Spine (Phila Pa 1976)*. 1999;24(20):2085-2090.
63. Lee TH, Park KS, Lee DG, Lee NG. Concurrent validity by comparing EMG activity between manual muscle testing, handheld dynamometer, and stationary dynamometer in testing of maximal isometric quadriceps contraction. *J Phys Ther Sci*. 2012;24(12):1219-1223.
64. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc*. 2004;36(6):926-934.
65. Le Gall F, Carling C, Reilly T, Vandewalle H, Church J, Rochcongar P. Incidence of injuries in elite French youth soccer players: a 10-season study. *Am J Sports Med*. 2006;34(6):928-938.
66. Li RT, Kling SR, Salata MJ, Cupp SA, Sheehan J, Voos JE. Wearable performance devices in sports medicine. *Sports Health*. 8(1):74-78.
67. Lorenz D, Morrison S. CURRENT CONCEPTS IN PERIODIZATION OF STRENGTH AND CONDITIONING FOR THE SPORTS PHYSICAL THERAPIST. *Int J Sports Phys Ther*. 2015;10(6):734-747.
68. Luomajoki H, Kool J, de Bruin ED, Airaksinen O. Reliability of movement control tests in the lumbar spine. *BMC Musculoskelet Disord*. 2007;8(1):90.
69. Madigan ML, Davidson BS, Nussbaum MA. Postural sway and joint kinematics during quiet standing are affected by lumbar extensor fatigue. *Hum Mov Sci*. 2006;25(6):788-799.
70. McCurdy K, O'Kelley E, Kutz M, Langford G, Ernest J, Torres M. Comparison of lower extremity EMG between the 2-leg squat and modified single-leg squat in female athletes. *J Sport Rehabil*. 2010;19(1):57-70.
71. McCurdy K, Walker J, Yuen D. Gluteus Maximus and Hamstring Activation During Selected Weight-Bearing Resistance Exercises. *J strength Cond Res*. 2018;32(3):594-601.
72. McGill SM. Core training: Evidence translating to better performance and injury prevention. *Strength Cond J*. 2010;32(3):33-46.
73. McGill SM, Childs A, Liebenson C. Endurance times for low back stabilization exercises: Clinical targets for testing and training from a normal database. *Arch Phys Med Rehabil*. 1999;80(8):941-944.

74. Meeuwisse WH, Tyreman H, Hagel B, Emery C. A Dynamic Model of Etiology in Sport Injury : The Recursive Nature of Risk and Causation. *Clin J Sport Med*. 2007;17(3):215-219.
75. Mentiplay BF, Perraton LG, Bower KJ, et al. Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: A reliability and validity study. *PLoS One*. 2015;10(10):1-18.
76. Mostaed MF, Werner DM, Barrios JA. 2D and 3D kinematics during lateral step-down testing in individuals with anterior cruciate ligament reconstruction. *Int J Sports Phys Ther*. 2018;13(1):77-85.
77. Nakagawa TH, Maciel CD, Serrão FV. Trunk biomechanics and its association with hip and knee kinematics in patients with and without patellofemoral pain. *Man Ther*. 2015;20(1):189-193.
78. Negrão Filho R de F, Silva LA, Monteiro TL, Alves N, de Carvalho AC, de Azevedo FM. Lumbo-pelvic stability and electromyography of abdominal muscles in ballet dancers. *Electromyogr Clin Neurophysiol*. 49(8):377-384.
79. Niemuth PE, Johnson RJ, Myers MJ, Thieman TJ. Hip muscle weakness and overuse injuries in recreational running. *Clin J Sport Med*. 2005;15(1):14-21.
80. O'Kane JW, Neradilek M, Polissar N, Sabado L, Tencer A, Schiff MA. Risk factors for lower extremity overuse injuries in female youth soccer players. *Orthop J Sport Med*. 2017;5(10):1-8.
81. O'Neill S, Watson PJ, Barry S. A Delphi study of risk factor for achilles tendinopathy - Opinions of world tendon experts. *Int J Sports Phys Ther*. 2016;11(5):684-697.
82. Parkhurst TM, Burnett CN. Injury and proprioception in the lower back. *J Orthop Sport Phys Ther*. 1994;19(5):282-295.
83. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star excursion balance test as a predictor of lower extremity injury in high school asketball players. *J Orthop Sport Phys Ther*. 2006;36(12):911-919.
84. Plsek PE, Greenhalgh T. Complexity science: The challenge of complexity in health care. *BMJ*. 2001;323(7313):625-628.
85. Plummer HA, Oliver GD. The relationship between gluteal muscle activation and throwing kinematics in baseball and softball catchers. *J strength Cond Res*. 2014;28(1):87-96.
86. Rabin A, Kozol Z. Measures of range of motion and strength among healthy women with differing quality of lower extremity movement during the lateral step-down test. *J Orthop Sports Phys Ther*. 2010;40(12):792-800.
87. Raschner C, Platzer HP, Patterson C, Werner I, Huber R, Hildebrandt C. The relationship between ACL injuries and physical fitness in young competitive ski racers: A 10-year longitudinal study. *Br J Sports Med*. 2012;46(15):1065-1071.
88. Rothman KJ. Causes. 1976. *Am J Epidemiol*. 1995;141(2):90-5; discussion 89.
89. Roussel NA, Nijs J, Mottram S, Van Moorsel A, Truijen S, Stassijns G. Altered lumbopelvic movement control but not generalized joint hypermobility is associated with increased injury in dancers. A prospective study. *Man Ther*. 2009;14(6):630-635.
90. Schuermans J, Danneels L, Van Tiggelen D, Palmans T, Witvrouw E. Proximal neuromuscular control protects against hamstring injuries in male soccer players: A prospective study with electromyography time-series analysis during maximal sprinting. *Am J Sports Med*. 2017;45(6):1315-1325.
91. Schuermans J, Van Tiggelen D, Palmans T, Danneels L, Witvrouw E. Deviating running kinematics and hamstring injury susceptibility in male soccer players: Cause or consequence? *Gait Posture*. 2017;57:270-277.
92. Silvers-Granelli H, Mandelbaum B, Adeniji O, et al. Efficacy of the FIFA 11+ injury prevention program in the collegiate male soccer player. *Am J Sports Med*. 2015;43(11):2628-2637.
93. Soomro N, Sanders R, Hackett D, et al. The efficacy of injury prevention programs in adolescent team sports: A meta-analysis. *Am J Sports Med*. 2016;44(9):2415-2424.
94. Souza RB, Powers CM. Predictors of hip internal rotation during running. *Am J Sports Med*. 2009;37(3):579-587.
95. Speirs DE, Bennett MA, Finn C V, Turner AP. Unilateral vs. Bilateral Squat Training for Strength, Sprints, and Agility in Academy Rugby Players. *J strength Cond Res*. 2016;30(2):386-392.
96. Stark T, Walker B, Phillips JK, Fejer R, Beck R. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: A systematic review. *PM R*. 2011;3(5):472-479.

97. Stevens VK, Bouche KG, Mahieu NN, Cambier DC, Vanderstraeten GG, Danneels LA. Reliability of a functional clinical test battery evaluating postural control, proprioception and trunk muscle activity. *Am J Phys Med Rehabil*. 2006;85(9):727-736.
98. Stevenson JH, Beattie CS, Schwartz JB, Busconi BD. Assessing the Effectiveness of Neuromuscular Training Programs in Reducing the Incidence of Anterior Cruciate Ligament Injuries in Female Athletes: A Systematic Review. *Am J Sports Med*. 2015;43(2):482-490.
99. Suter E, Lindsay D. Back muscle fatigability is associated with knee extensor inhibition in subjects with low back pain. *Spine (Phila Pa 1976)*. 2001;26(16):E361-E66.
100. Teng H-L, Powers CM. Hip-extensor strength, trunk posture, and sse of the knee-extensor muscles during running. *J Athl Train*. 2016;51(7):519-524.
101. Thorborg K, Petersen J, Magnusson SP, Hölmich P. Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scand J Med Sci Sport*. 2010;20(3):493-501.
102. Van Dyk N, Witvrouw E, Bahr R. Interseason variability in isokinetic strength and poor correlation with Nordic hamstring eccentric strength in football players. *Scand J Med Sci Sports*. 2018;28(8):1878-1887.
103. Van Gelder LH, Hoogenboom BJ, Alonzo B, Briggs D, Hatzel B. EMG Analysis and Sagittal Plane Kinematics of the Two-Handed and Single-Handed Kettlebell Swing: A Descriptive Study. *Int J Sports Phys Ther*. 2015;10(6):811-826.
104. Van Tiggelen D, Wickes S, Stevens V, Roosen P, Witvrouw E. Effective prevention of sports injuries: A model integrating efficacy, efficiency, compliance and risk-taking behaviour. *Br J Sports Med*. 2008;42(8):648-652.
105. Vercruysse S, Haerens L, Verhagen E, Goossens L, De Clercq D. Effects of a multifactorial injury prevention intervention in physical education teachers: A randomized controlled trial. *Eur J Sport Sci*. 2016;16(7):868-876.
106. Verrelst R, De Clercq D, Vanrenterghem J, Willems T, Palmans T, Witvrouw E. The role of proximal dynamic joint stability in the development of exertional medial tibial pain: A prospective study. *Br J Sports Med*. 2014;48(5):388-393.
107. Weir A, Darby J, Inklaar H, Koes B, Bakker E, Tol JL. Core stability: inter- and intraobserver reliability of 6 clinical tests. *Clin J Sport Med*. 2010;20(1):34-38.
108. Wilkerson GB, Colston MA. A refined prediction model for core and lower extremity sprains and strains among collegiate football players. *J Athl Train*. 2015;50(6):643-650.
109. Wilkerson GB, Giles JL, Seibel DK. Prediction of core and lower extremity strains and sprains in collegiate football players: A preliminary study. *J Athl Train*. 2012;47(3):264-272.
110. Willardson JM. Core stability training: applications to sports conditioning programs. *J Strength Cond Res*. 2007;21(3):979-985.
111. Willson JD, Ireland ML, Davis I. Core strength and lower extremity alignment during single leg squats. *Med Sci Sports Exerc*. 2006;38(5):945-952.
112. Wright SP, Hall Brown TS, Collier SR, Sandberg K. How consumer physical activity monitors could transform human physiology research. *Am J Physiol Regul Integr Comp Physiol*. 2017;312(3):R358-R367.
113. Zazulak B, Cholewicki J, Reeves NP. Neuromuscular control of trunk stability: Clinical implications for sports injury prevention. *J Am Acad Orthop Surg*. 2008;16(9):497-505.
114. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: A prospective biomechanical-epidemiologic study. *Am J Sports Med*. 2007;35(7):1123-1130.
115. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med*. 2007;35(3):368-373.
116. Zhang ZJ, Lee WC, Ng GYF, Fu SN. Isometric strength of the hip abductors and external rotators in athletes with and without patellar tendinopathy. *Eur J Appl Physiol*. 2018;118(8):1635-1640.

NEDERLANDSE SAMENVATTING
LIST OF ABBREVIATIONS
ACKNOWLEDGEMENTS | DANKWOORD
CURRICULUM VITAE

Nederlandse samenvatting

Het optrainen van 'romp, lumbopelvische en heup stabiliteit', of kortweg '**rompstabiliteit**', heeft het laatste decennium enorm veel aan populariteit gewonnen en wordt soms omschreven als de hoeksteen voor elke vorm van training. De term 'rompstabiliteit' dekt echter niet steeds de volledige lading wanneer men naar de praktische invulling van dit gegeven kijkt. Binnen het kader van deze uiteenzetting wordt rompstabiliteit als volgt omschreven:

'Rompstabiliteit, gevormd door dynamische romp, lumbopelvische en heupstabiliteit, is de basis voor het produceren, controleren en geleiden van kracht en beweging doorheen de kinetische keten tijdens bewegen. Om rompstabiliteit te verwerven maken we gebruik van verschillende musculoskeletale eigenschappen die optimaal moeten samenwerken, waaronder rompspierkracht, spierkrachtuithouding, proprioceptie en neuromusculaire controle. Vanuit een anatomisch standpunt zijn de beenderige en weke delen elementen van de romp, lumbopelvische en heupregio betrokken voor het verwerven van rompstabiliteit. Adequate rompstabiliteit resulteert in veilig en gecontroleerd bewegen distaal van de romp en levert aldus een belangrijke bijdrage om dynamische gewrichtsstabiliteit te onderhouden doorheen de kinetische keten.'

Het trainen van rompstabiliteit heeft reeds zijn nut bewezen in de rehabilitatie van lage rugpijn patiënten en in het verbeteren van atletische prestaties. De laatste jaren echter wordt er steeds meer aandacht besteed aan de rol van ontoereikende rompstabiliteit in het ontwikkelen van musculoskeletale letsels van het onderste lidmaat. Immers, als adequate rompstabiliteit zorgt voor gecontroleerde bewegingen doorheen de kinetische keten, kan slechte rompstabiliteit dan resulteren in compensatoire bewegingen doorheen de kinetische keten en aldus een rol spelen in het oplopen van letsels van het onderste lidmaat?

Deze stelling werd gebruikt als uitgangspunt om dit doctoraatsproject uit te werken met als einddoel meer inzicht te verwerven in het complexe concept van de rompstabiliteit, hoe het geëvalueerd kan worden en wat de associatie is met letsels van het onderste lidmaat. Om op deze vragen te antwoorden werd in **hoofdstuk I** een systematische review uitgevoerd van de beschikbare literatuur met rompstabiliteit als risicofactor voor letsels aan het onderste lidmaat als onderwerp. In deze systematische review werd beperkt bewijs gevonden voor ontoereikende rompspierkracht, proprioceptie en neuromusculaire controle van de romp in het ontwikkelen van letsels aan het onderste lidmaat. Daarenboven werd er tegenstrijdig bewijs gevonden voor de uithoudingscapaciteit van de rompspieren als risicofactor voor letsels onderste lidmaat en werd er over het algemeen geconcludeerd dat er beperkt bewijs is in de huidige literatuur die de associatie tussen ontoereikende rompstabiliteit en overbelastingsletsels van het onderste lidmaat aantoont.

Om meer inzicht te verwerven in hoe rompstabiliteit kan gemeten worden, werd er in **hoofdstuk II** onderzoek gevoerd naar verschillende testen die het functioneren nagaan van de verschillende aspecten waar stabiliteit van de romp uit voortkomt. Dit had als einddoel het samenstellen van veldtesten die we kunnen gebruiken om deze verschillende aspecten van rompstabiliteit te testen op een betrouwbare en valide manier in een gezonde populatie. Om deze resultaten makkelijk te vertalen naar de klinische praktijk is het noodzakelijk om te voorzien in testen die op een eenvoudige en betrouwbare manier uitgevoerd kunnen worden zonder het gebruik van veel extra dure materialen. De planktest, een test die de uithoudingscapaciteit van de buikspieren meet, werd al valide en betrouwbaar bevonden op basis van elektromyografische metingen. Ten tweede werd het meten van de kracht van de rompbuigers en rompstrekkers met behulp van een in de hand gehouden dynamometer ook als valide en betrouwbaar beschouwd door deze metingen te vergelijken met een commerciële stabiele dynamometer. Ten slotte werd ook de betrouwbaarheid van twee nieuwe meetmethoden bevestigd, namelijk de lumbopelvische positie-repositie test en de laterale trap af test. Deze testen werden aldus opgenomen in de testbatterij naast andere valide en betrouwbare testen die reeds gebruikt worden om verschillende aspecten van rompstabiliteit te meten.

Door de hoge incidentie van overbelastingsletsels aan het onderste lidmaat enerzijds en door het nog steeds ontbrekende inzicht in de ontstaansmechanismen van deze letsels en de risicofactoren hiervoor, zijn we in **hoofdstuk III** nagegaan wat de associatie is tussen ontoereikende rompstabiliteit en het ontwikkelen van overbelanstingsletsels aan het onderste lidmaat. Om deze associatie te kunnen aantonen werd een prospectieve studie opgestart waarbij gezonde actieve participanten de testbatterij voor rompstabiliteit uitvoerden waarna ze gedurende 2 jaar opgevolgd werden en het ontstaan van letsels werd geregistreerd. Deze studie identificeerde het voorkomen van gedaalde uithoudingscapaciteit van de buikspieren, een gedaalde ratio voor isometrische heupbuig/heupstrekkracht, gecombineerd met een links/rechts asymmetrie in posturale controle als een significante risicofactor voor het oplopen van overbelastingsletsels van het onderste lidmaat.

Hoewel deze resultaten bewijs leveren voor de rol van rompstabiliteit in het oplopen van musculoskeletale letsels, en deze resultaten eenvoudig kunnen vertaald worden naar de klinische praktijk, dient er nog veel onderzoek uitgevoerd te worden om een volledig inzicht in deze materie te verwerven.

List of abbreviations

BMI	Body Mass Index
BF	Biceps Femoris
CI	Confidence Interval
EMG	Electromyography
EO	External Oblique
FFT	Fast Fourier Transforms
HHD	Handheld Dynamometry
Hz	Hertz
ICC	Intraclass Correlation Coefficient
i.e.	id est
IO	Internal Oblique
ILT	Iliocostalis Lumborum Pars Thoracis
LEI	Lower Extremity Injury
LEOI	Lower Extremity Overuse Injury
MDC	Minimal Detectable Change
MF	Multifidus
MF_{slope}	Median Frequency Slope
MMT	Manual Muscle Testing
MVIC	Maximum Voluntary Isometric Contraction
NMF	Normalized Median Frequency
NMF_{slope}	Normalized Median Frequency Slope
RA	Rectus Abdominis
RF	Rectus Femoris
ROM	Range Of Motion
SD	Standard Deviation
SEM	Standard Error of Measurement
sEMG	Surface Electromyography
SPSS	Statistical Package for the Social Sciences
3D	three-dimensional

ACKNOWLEDGEMENTS | DANKWOORD

Na zes mooie jaren REVAKI sta ik hier vandaag om mijn project te finaliseren. Na deze enorm leerrijke en uitdagende periode kan ik mij geen betere manier bedenken om het hoofdstuk PhD af te sluiten, dan door de talrijke mensen te bedanken, die samen met mij de realisatie van dit project ondersteund hebben.

Graag richt ik mij eerst tot (prof. dr.) Philip (Roosen). Ik wil je bedanken voor de kans die je mij gegeven hebt om dit project uit te voeren. Van bij de start heb jij me de vrijheid gegeven om de lijnen van dit onderzoek uit te zetten en op ontdekking te gaan. Samen botsten we op dit uitermate boeiend onderwerp waarop ik mij volledig kon storten. Vrijheid en ruimte krijgen om zelfstandig te werken is niet steeds gemakkelijk, maar deze aanpak heeft er wel voor gezorgd dat ikzelf over de 6 jaar heen enorm geëvolueerd en gegroeid ben, op alle mogelijke vlakken. Ik kan dan ook met trots zeggen dat dit naast 'ons' project toch ook echt 'mijn' project geworden is. Bedankt voor steeds in mij te blijven geloven en er altijd te zijn voor raad, ook op de moeilijke momenten.

Zonder steun van mijn begeleidingscommissie zou mijn werk er niet uitzien zoals ik het vandaag kan presenteren. Bedankt prof. (dr.) Lieven Danneels en prof. (dr.) Luc Vanden Bossche voor jullie wetenschappelijke inzichten, enorme expertise en raad bij specifieke problemen. Ook niet te vergeten is jullie aanwezige enthousiasme bij goed nieuws en de constante motivatie om verder te blijven volhouden.

Prof. (dr.) Tine Willems, hoewel jij slechts later aansloot bij mijn begeleidingscommissie, ben je van onmiskenbaar belang gebleken voor mijn project. Door jouw efficiënte werkstijl, oprechte interesse en statistisch inzicht heeft mijn onderzoek een extra dimensie gekregen.

Last but not least, (dr.) Roel (De Ridder). Desondanks dat ook jij slechts later mijn co-promotor geworden bent, heb je een enorm groot aandeel gehad in dit project. Jij was het die mij in het begin toch de nodige discipline bijbracht en me wees op mijn plichten, wat soms echt nodig was. Maar ik heb vooral het gevoel dat jij mij echt hebt kunnen begeleiden en sturen gedurende het hele proces tot op de dag van vandaag. Voor de meest triviale zaken kon ik bij u terecht, nooit was iets teveel gevraagd en de oplossingen stonden steeds klaar. Merci!

Ook de examencommissie wil ik nogmaals bedanken voor de tijd die zij genomen hebben om op een kritische manier mijn werk te lezen en te beoordelen. Prof. dr. Patrick Calders, prof. dr. Christophe Demoulin, prof. dr. Nathalie Roussel, dr. Veerle Stevens, dr. Lennert Goossens en prof. dr. Ruth Verrelst, many thanks for your relevant and constructive criticism during the final phase of this project.

Merci aan alle collega's van het eerste, tweede en derde verdiep voor jullie collegialiteit de afgelopen zes jaar. Het zijn er teveel om allemaal te bedanken, maar zoveel vriendschappelijke en professionele ondersteuning zorgde voor een aangename werkomgeving waar ik steeds met zoveel plezier naar terugkeerde. Extra dank voor de mannen van de vissersbureau! Vincent, Stijn en Damien. Naast het ijverig gevis, zal ik ons vele gezever en gezwans enorm missen!

Tot slot wil ik heel graag al mijn vrienden en familie bedanken! Merci boys, om mij altijd te laten beseffen wat echt belangrijk is! Samen plezier maken, samen trainen, feesten, board game nights, en sneakerbeurzen doen! Ook mama, papa, Matthias, Esther en de twee kleine monsterkes, Alex en Sam. Merci, niet alleen voor jullie steun de afgelopen jaren maar eigenlijk voor al de steun en motivatie die ik al heel mijn leven van jullie krijg. Altijd staat de deur open bij jullie in Sint-Niklaas en soms laat ik het niet altijd blijken, maar ik apprecieer jullie hulp heel hard!

Daphs, jij hebt het grootste deel van mijn project van dichtbij kunnen volgen. Jij was erbij voor alle ups en downs. Jij was er steeds voor alles te relativeren en om mij te blijven motiveren. Zo hard dat ge zelf werkt, zo hard hebt ge mij geholpen, zeker in deze laatste periode. Gij hebt mij altijd gesteund door gewoon te zijn wie ge zijt en, bij u kan ik pas echt tot rust komen! Wij zijn zo een goed team en ik kijk al uit naar wat de toekomst ons zal brengen!

PS: Thanks Frederik Vanhoutte om zomaar je kunstwerken beschikbaar te stellen zodat ik ze kon gebruiken voor mijn cover!

Curriculum vitae

General information

Name	Cedric De Blaiser
Date of birth	09.02.1988
Place of birth	Sint-Niklaas
Nationality	Belgian
Private Address	Spitaalpoortstraat 1C-001, 9000 Ghent, Belgium
Phone	+32 485.112.149
E-mail	cedricdeblaiser@gmail.com
Driver's licence	B
Marital status	Unmarried

Education

2013 – 2019 (ongoing)

PhD in Health Sciences, Department of Rehabilitation Sciences, Faculty of Medicine and Health Sciences, Ghent University

PhD Thesis: *"Core stability: Clinical assessment tools and the role of core stability in the development of lower extremity injuries."*

2012

Master of Health Science in Rehabilitation Sciences and Physiotherapy (major Musculoskeletal Rehabilitation), degree attained cum laude

Master thesis: *"Development of a classification for static and dynamic lower extremity alignment based on 3D movement analysis."*

2010

Bachelor in Rehabilitation Sciences and Physiotherapy, degree attained cum laude

Bachelor thesis: *"Development of a normative database for test scores on the SOS writing test in preliminary education"*

2006 – 2007

Bachelor of Science in Pharmaceutical Sciences (degree not attained)

Additional courses and training

Practical training – Profession related

"An integrative and up-to-date approach to ankle and foot related complaints" (2013), Instituut voor Permanente Vorming, REVAKI, Ghent University
"Qualisys User Meeting" (2013), Exave AB, Erlangen, Germany
"ComplexCore: Training and Therapy (2013), Faculty of Kinesiology and Rehabilitation Sciences, University of Leuven
"Medical Exercise Therapy" (2014), Instituut voor Permanente Vorming, REVAKI, Ghent University
"Hydrotherapy, a hands-on course" (2015), Vlaamse Vereniging voor Sportgeneeskunde

Academic Transferrable Skills Courses

"Cursus Basisdocententraining (2017), Doctoral Schools of Life Science and Medicine, Ghent University"
"Knowledge 2 Connect courses (2013-2018), Seminar organized by Kenniscentrum voor de Gezondheidszorg Gent (KCGG). Topics included:

- Why (also) use Embase as source for biomedical literature? A comparison with MEDLINE/PubMed and advanced searching techniques in Embase.
- How can I turn my manuscripts into an Article?
- How to get your message across effectively: the science of storytelling.
- Research integrity

Professional experience

Clinical/academic experience

July – August 2012
Interim physical therapist (Clinical practice Evert De Witte)
September – October 2012
Interim teaching assistant Department of Rehabilitation Sciences and Physical Therapy, Ghent University

Teaching

2012 – Present
Teaching at the Department of Rehabilitation Sciences and Physiotherapy, Faculty of Medicine and Health Sciences, Ghent University
(1) Physiotherapeutical assessment: Lower Limb (1st Bachelor)
(2) Physiotherapeutical assessment: Upper Limb (1st Bachelor)
(3) Introduction to clinical placement (2nd Bachelor)
(4) Physical means in Physical therapy and Rehabilitation (2nd Bachelor)
(5) Scientific project in Rehabilitation Sciences and Physiotherapy (3rd Bachelor)
(6) Screening and Evaluation (1st Master)
(7) Clinical reasoning (1st Master)
(8) Sports physical therapy (2nd Master)
(9) Clinical placement supervision (3rd Bachelor, 1st Master, 2nd Master)
(10) Master thesis supervision (1st Master, 2nd Master)

Publications

De Blaiser C, Roosen P, Willems T, Danneels L, Bossche L Vanden, De Ridder R. Is core stability a risk factor for lower extremity injuries in an athletic population? A systematic review. Phys Ther Sport. 2018;30:48-56. doi:10.1016/j.ptsp.2017.08.076.

De Blaiser C, De Ridder R, Willems T, Danneels L, Vanden Bossche L, Palmans T, Roosen P. Evaluating abdominal core muscle fatigue: Assessment of the validity and reliability of the prone bridging test. Scand J Med Sci Sports. 2018;28(2):391-399. doi:10.1111/sms.12919.

De Pauw R, Kregel J, **De Blaiser C**, Van Akeleyen J, Logghe T, Danneels L, Cagnie B. Identifying prognostic factors predicting outcome in patients with chronic neck pain after multimodal treatment: a retrospective study. Man Ther. 2015;20(4):592-597. doi:10.1016/j.math.2015.02.001.

De Blaiser C, De Ridder R, Willems T, Danneels L, Roosen R. Reliability and validity of trunk flexor and trunk extensor strength measurements using handheld dynamometry in a healthy athletic population. *Phys Ther Sport*. 2018;34:180-186. doi: 10.1016/j.ptsp.2018.10.005.

De Blaiser C, De Ridder R, Willems T, Danneels L, Roosen R. Reliability of two functional clinical tests to evaluate trunk and lumbopelvic neuromuscular control and proprioception in a healthy population [published online ahead of print November 10, 2018]. *Br J Phys Ther.* doi:10.1016/j.bjpt.2018.10.014.

De Blaiser C, De Ridder R, Willems T, Vanden Bossche L, Danneels L, Roosen P. Impaired core stability as a risk factor for the development of lower extremity overuse injuries: A prospective cohort study. First round revision, American Journal of Sports Medicine.

De Ridder R, Willems T, Vanrenterghem J, Verrelst R, **De Blaiser C**, Roosen P (in press). Taping benefits ankle joint loading kinematics in subjects with chronic ankle instability. *J Sport Rehabil*.

De Ridder R, **De Blaiser C**. Activity trackers are not valid for step count registration when walking with crutches. First round revision, Gait & Posture.

De Ridder R, Lebleu J, Willems T, **De Blaiser C**, Detrembleu C, Roosen P. Concurrent validity of a commercial wireless trunk tri-axial accelerometer system for gait analysis. First round revision, Journal of Sport Rehabilitation.

International presentations

Poster presentations

"Is core stability a risk factor for lower extremity injuries in an athletic population? A systematic review." World Congress of Physical Therapy – Cape Town – 02.07 – 04.07 2017

Oral presentations

"The development of lower limb overuse injuries: A deeper look into intrinsic risk factors" (2015). Invited speaker Kine kring Aalst.

"Core stability and its relationship to lower extremity injuries". (2017) Invited speaker Multidisciplinary VVS congress, Vlaamse Vereniging voor Sportgeneeskunde.

"Core muscle endurance as a risk factor for the development of lower extremity muscle strains. A prospective study." World Congress of Physical Therapy – Cape Town – 02.07 – 04.07 2017

"Evaluating abdominal core muscle fatigue: assessment of the validity and reliability of the prone bridging test." World Congress of Physical Therapy – Cape Town – 02.07 – 04.07 2017

Membership and associations

2014 – Present
Member of the Spine Research Unit Ghent. Department of Rehabilitation, Ghent University

Knowledge of languages

Dutch	Native
English	Very Good
French	Basic
German	Basic

General interests

Sports in general
Sneakers and fashion
Music (drums)
Comics, graphic novels and manga
Tabletop gaming and computer gaming
Animals