

ANU RÄISÄNEN

The background of the cover features a collection of blue, semi-transparent spheres of various sizes. These spheres are scattered across the white background, with some appearing in the foreground and others receding into the distance, creating a sense of depth. The spheres have a slightly textured surface, resembling marbles or bubbles.

Adolescent Sports Injuries

Frontal plane knee control
as an injury risk factor and a screening tool



ANU RÄISÄNEN

Adolescent Sports Injuries

Frontal plane knee control
as an injury risk factor and a screening tool



ACADEMIC DISSERTATION

To be presented, with the permission of
the Faculty Council of Social Sciences
of the University of Tampere, for public discussion
in the auditorium F115 of the Arvo building,
Arvo Ylpön katu 34, Tampere,
on 17 May 2018, at 12 o'clock.

UNIVERSITY OF TAMPERE

ANU RÄISÄNEN

Adolescent Sports Injuries

Frontal plane knee control
as an injury risk factor and a screening tool

Acta Universitatis Tamperensis 2369
Tampere University Press
Tampere 2018



UNIVERSITY
OF TAMPERE

ACADEMIC DISSERTATION

University of Tampere, Faculty of Social Sciences

UKK Institute for Health Promotion Research, Tampere Research Center of Sports Medicine
Finland

Supervised by

Professor Arja Rimpelä
University of Tampere
Finland
Docent Jari Parkkari
University of Tampere
Finland

Reviewed by

Professor Carolyn Emery
University of Calgary
Canada
Docent Timo Järvelä
University of Tampere
Finland

The originality of this thesis has been checked using the Turnitin OriginalityCheck service
in accordance with the quality management system of the University of Tampere.

Copyright ©2018 Tampere University Press and the author

Cover design by
Mikko Reinikka

Acta Universitatis Tamperensis 2369
ISBN 978-952-03-0720-2 (print)
ISSN-L 1455-1616
ISSN 1455-1616

Acta Electronica Universitatis Tamperensis 1875
ISBN 978-952-03-0721-9 (pdf)
ISSN 1456-954X
<http://tampub.uta.fi>

Suomen Yliopistopaino Oy – Juvenes Print
Tampere 2018



*To my loving family
Thank you for always believing in me*

ABSTRACT

The purpose of this doctoral dissertation was to explore the role of frontal plane knee control as a risk factor for lower extremity injury among young team-ball-sport athletes. In addition, the goal was to investigate whether the single-leg squat test, analysed using a two-dimensional video analysis method, can be used to screen for athletes with an elevated risk of future lower extremity injury. Furthermore, another objective was to explore whether age, sex, and side-to-side differences exist in frontal plane knee control.

The first step in this process was to investigate the extent of physical activity-related injuries in an adolescent population in Finland (Study I). The results demonstrated that this is a major public health issue, with every third adolescent becoming injured at least once during a one-year period. The problem was most prevalent in the sports club setting, followed by leisure time physical activity and school sports.

Visual assessment of the single-leg squat performance is used as a clinical tool to assess frontal plane knee control. In Study II, the intra-rater and inter-rater reliability of the visual assessment were explored, as well as the agreement between the visual assessment and the two-dimensional video analysis of the single-leg squat performance. The intra-rater reliability improved during the three-year study period. The inter-rater reliability between a novice and an experienced observer was poor to fair. The findings indicate that the visual assessment on a 3-point graded scale can be used to detect differences in frontal plane knee control; however, the expertise of the person performing the visual assessment is crucial for reliability.

Frontal plane knee control as a risk factor was investigated among a cohort of young (mean age 15.7 years) basketball and floorball players (Study III) and 10- to 14-year-old football players (Study IV). Frontal plane knee control was described by the frontal plane knee projection angle (FPKPA) measured based on the single-leg squat performance using the two-dimensional video analysis method. Among the basketball and floorball players, athletes with poor frontal plane knee control were 2.7-times more likely to sustain acute lower extremity injury and 2.4-times more likely to sustain acute ankle injury compared to athletes with intermediate

knee control. Among the young football players, knee control was not associated with the risk of lower extremity injuries.

The potential of the single-leg squat performance, described by FPKPA, to be used as a screening tool to identify athletes with an elevated risk of lower extremity injuries was investigated in Study III. The poor combined sensitivity and specificity indicate that the FPKPA is not a suitable tool to screen for athletes at high risk.

The effects of sex, age, and leg dominance were investigated in Studies III and IV. There were no significant differences in the mean FPKPA between sexes when analysing the entire cohorts. Among floorball and basketball players, there were significant sex differences among the older (>15.7 years) players: boys displayed better knee control than girls. Age was associated with knee control among the 10 to 14-year-old football players: older players displayed better knee control. Among the basketball and floorball players, older boys displayed better knee control than did younger boys. There were no differences in knee control between younger and older girls. There were significant differences in knee control between the dominant and non-dominant leg among the young football players: knee control was better for the non-dominant leg. Side-to-side differences between dominant and non-dominant leg were not detected among the cohort of basketball and floorball players, but boys displayed significantly greater mean FPKPA on the right leg compared to the left.

The results in this doctoral dissertation highlight the importance of implementing more effective injury prevention methods to reduce the public health burden of adolescent physical activity-related injuries in Finland. Furthermore, the results indicate that adequate frontal plane knee control is essential to reduce the risk of lower extremity injuries in team-sport athletes. The single-leg squat can be used to assess frontal plane knee control to determine if an athlete requires further training. However, the single-leg squat performance does not predict whether an individual will experience an injury.

TIIVISTELMÄ

Tämän väitöskirjan tarkoituksena oli selvittää frontaalitason polvenhallinnan roolia alaraajavammojen riskitekijänä nuorilla palloilulajien harrastajilla. Lisäksi tavoitteena oli selvittää voiko yhden jalan kyykky -testiä, analysoituna kaksikulotteisella videoanalyysillä, käyttää seulontatestinä tunnistamaan urheilijat, joilla on kohonnut riski saada alaraajavammoja tulevaisuudessa. Edelleen tavoitteena oli selvittää polvenhallinnassa ilmeneviä ikään ja sukupuoleen liittyviä eroja ja alaraajojen välisiä puolieroja.

Ensimmäisessä vaiheessa, osatyössä I, selvitettiin liikuntavammojen yleisyyttä suomalaisilla nuorilla. Tulokset osoittavat, että nuorten liikuntavammat ovat merkittävä kansanterveysongelma: joka kolmas nuori oli loukkaantunut liikunnan parissa vähintään kerran edellisen vuoden aikana. Liikuntavammat olivat yleisimpiä urheiluseuraliikunnassa, jonka jälkeen vapaa-ajan liikunnassa ja koululiikunnassa.

Frontaalitason polvenhallinnan visuaalista arviointia yhden jalan kyykky -testissä käytetään kliinisessä työssä polvenhallinnan arviointiin. Osatyössä II selvitettiin visuaalisen arvioinnin luotettavuutta sekä arviointikertojen että arvioitsijoiden välillä. Lisäksi tutkittiin visuaalisen arvioinnin ja kaksikulotteisella videoanalyysillä mitatun frontaalitason polvikulman korrelaatiota yhden jalan kyykky -testissä. Arviointikertojen välinen luotettavuus parani kolmen vuoden tutkimusjakson aikana. Arvioitsijoiden välinen luotettavuus aloittelijan ja kokeneen arvioitsijan välillä oli huono/kohtuullinen. Tulokset osoittavat, että visuaalista arviointia kolmiportaisella asteikolla voidaan käyttää havainnoimaan eroja frontaalitason polvenhallinnassa, mutta arvioinnin suorittajan riittävä kokemus on välttämätöntä luotettavien tulosten saamiseksi.

Frontaalitason polvenhallintaa mahdollisena riskitekijänä tutkittiin nuorilla (keski-ikä 15,7 vuotta) salibandyn ja koripallon pelaajilla (osatyö III) ja 10–14-vuotiailla jalkapalloilijoilla (osatyö IV). Frontaalitason polvenhallintaa kuvattiin frontaalitason projektiokulmalla, joka mitattiin yhden jalan kyykky -testistä kaksikulotteista videoanalyysia käyttäen. Nuorilla salibandyn ja koripallon pelaajilla huono polvenhallinta oli yhteydessä vammoihin. Pelaajilla, joiden frontaalitason projektiokulma oli suuri, oli 2,7-kertainen todennäköisyys alaraajavammoihin ja 2,4-kertainen todennäköisyys nilkkavammoihin verrattuna pelaajiin, joilla projektiokulma

oli keskitasoa. Nuorilla jalkapalloilijoilla polvenhallinta ei ollut yhteydessä alaraajavammoihin.

Yhden jalan kyykky -testin potentiaalia seuloa nuorista urheilijoista ne, joilla on kohonnut riski vammoihin, selvitettiin kolmannessa osatyössä. Testin huono sensitiivisyys ja spesifisyys osoittavat, että yhden jalan kyykky -testissä mitattu frontaalitason projektiokulma ei ole toimiva seulontatyökalu kohonneen loukkaantumisriskin tunnistamiseen.

Osatöissä III ja IV selvitettiin ikään ja sukupuoleen liittyviä eroja polvenhallinnassa. Lisäksi tutkittiin alaraajojen välisiä puolieroja polvenhallinnassa. Tutkittaessa koko kohortteja, sukupuolten välillä ei ollut merkitseviä eroja frontaalitason projektiokulmassa. Salibandyn ja koripallon pelaajilla havaittiin, että vanhempien pelaajien (yli 15,7 vuotta) joukossa pojilla polvenhallinta oli parempaa kuin tytöillä. Ikään liittyviä eroja havaittiin 10–14-vuotiailla jalkapalloilijoilla: vanhemmilla pelaajilla oli parempi polvenhallinta. Salibandyn ja koripallon pelaajilla havaittiin, että vanhemmilla pojilla (>15,7 vuotta) polvenhallinta oli parempi kuin nuoremmilla. Tytöillä ei havaittu ikään liittyviä eroja salibandyn ja koripallon pelaajilla. Dominoivan ja ei-dominoivan jalan välillä havaittiin merkitseviä eroja nuorilla jalkapalloilijoilla: polvenhallinta oli parempaa ei-dominoivalla jalalla. Puolieroja dominoivan ja ei-dominoivan jalan välillä ei havaittu salibandyn ja koripallon pelaajilla, mutta pojilla oikean jalan polvenhallinta oli huonompaa kuin vasemman.

Tämä väitöskirja tuo esille, kuinka tärkeää on panostaa liikuntavammojen ehkäisyyn, jotta vammojen aiheuttamaa kuormaa kansanterveydelle Suomessa voidaan vähentää. Lisäksi tulokset osoittavat, että riittävä frontaalitason polvenhallinta on tärkeää nuorille palloilijoille vammatariskin pienentämiseksi. Yhden jalan kyykky -testi on toimiva työkalu polvenhallinnan arviointiin ja tuloksen perusteella urheilijaa voidaan opastaa sopivien harjoitteiden käytössä polvenhallinnan parantamiseksi. Testitulokset ei kuitenkaan ennusta, kuka tulee loukkaantumaan.

LIST OF ORIGINAL PUBLICATIONS

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals. In addition, some unpublished data are presented.

- I Räsänen A, Parkkari J, Karhola L, Rimpelä A. Adolescent physical activity-related injuries in sports club, school sports and other leisure time physical activities. *Cogent Medicine* 2016;3:1260786.
- II Räsänen A, Pasanen K, Krosshaug T, Avela J, Perttunen J, Parkkari J. Single-leg squat as a tool to evaluate young athlete's frontal plane knee control. *Clinical Journal of Sports Medicine* 2016;26:478–82.
- III Räsänen AM, Pasanen K, Krosshaug T, Vasankari T, Kannus P, Heinonen A, Kujala UM, Avela J, Perttunen J, Parkkari J. Association between frontal plane knee control and lower extremity injuries: A prospective study on young team sport athletes. *BMJ Open Sport & Exercise Medicine* 2018;4:e000311.
- IV Räsänen AM, Arkkila H, Vasankari T, Steffen K, Parkkari J, Kannus P, Forsmann H, Pasanen K. Investigation of knee control as a lower extremity injury risk factor: A prospective study in youth football. *Scandinavian Journal of Medicine & Science in Sports*. *In press*.

Studies I and III are reproduced in accordance with the Creative Commons Attribution licence. Permissions to append Studies II and IV to the doctoral dissertation were kindly granted by the publishers.

ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
ACL	anterior cruciate ligament
AHLS	Adolescent Health and Lifestyle Survey
ASIS	anterior superior iliac spine
AUC	area under the curve
BMI	body mass index
CI	confidence interval
EMG	electromyography
FMS TM	Functional Movement Screen TM
FPKPA	frontal plane knee projection angle
IPEP	injury prevention exercise program
LESS	Landing Error Scoring System
OR	odds ratio
PA	physical activity
PFPS	patella-femoral pain syndrome
PHV	peak height velocity
PROFITS	Predictors of Lower Extremity Injuries in Team Sport
ROC	receiver operating characteristics
ROM	range of motion
SD	standard deviation
SEBT	star excursion balance test
SLS	single-leg squat
SLVDJ	single-leg vertical drop jump
U11	under 11 years
U12	under 12 years
U13	under 13 years
U14	under 14 years
VDJ	vertical drop jump

TABLE OF CONTENTS

1	INTRODUCTION.....	15
2	REVIEW OF LITERATURE.....	17
2.1	Adolescent sports injuries as a public health issue.....	17
2.2	Sports injury risk factors in adolescence.....	19
2.2.1	Non-modifiable extrinsic risk factors	19
2.2.2	Potentially modifiable extrinsic risk factors.....	20
2.2.3	Non-modifiable intrinsic risk factors.....	22
2.2.4	Potentially modifiable intrinsic risk factors	24
2.3	Knee valgus and frontal plane knee control.....	26
2.3.1	Frontal plane knee control.....	26
2.3.2	Factors contributing to frontal plane knee control	27
2.3.3	Frontal plane knee control and injuries.....	28
2.4	Screening tools to predict lower extremity injuries in adolescent athletes	30
2.4.1	Screening as a concept.....	30
2.4.2	Star excursion balance test.....	32
2.4.3	Vertical drop jump	33
2.4.4	Functional movement screen.....	34
2.4.5	Strength measures	36
2.4.6	Predictive value of screening tests.....	36
2.5	The single-leg squat test.....	43
2.5.1	Validity and reliability of the two-dimensional analysis.....	43
2.5.2	Frontal plane knee control during the single-leg squat.....	43
2.5.3	Visual assessment	45
2.5.4	Range of motion.....	47
2.5.5	Single-leg squat performance in adolescents	47
2.5.6	Differences related to sex	48
2.5.7	Patients with patella-femoral pain syndrome	48
2.5.8	Patients with an ACL injury	49
2.5.9	Correlation with other screening tests.....	50
2.5.10	Differences in the SLS test protocols and interpretation.....	50
2.6	Limitations in previous prospective injury risk factor studies.....	51
3	PURPOSE OF THE STUDY	55
4	MATERIALS AND METHODS.....	57

4.1	Adolescent physical activity-related injuries (I).....	57
4.1.1	Study design and subjects.....	57
4.1.2	Outcomes and data collection.....	58
4.2	Visual assessment of the single-leg squat performance (II).....	59
4.2.1	Study design and subjects.....	59
4.2.2	Outcomes and data collection.....	60
4.3	Knee control and injury risk in young floorball and basketball players (III).....	63
4.3.1	Study design and subjects.....	63
4.3.2	Outcomes and data collection.....	63
4.4	Knee control and injury risk in youth football players (IV).....	65
4.4.1	Study design and subjects.....	65
4.4.2	Outcomes and data collection.....	65
4.5	Statistical methods	66
4.6	Contribution statement	68
5	RESULTS	70
5.1	Adolescent physical activity-related injuries (I).....	70
5.1.1	Subjects	70
5.1.2	Injury prevalence in sports club activities, school sports, and leisure time PA	71
5.1.3	PA participation frequency, intensity, and injury prevalence	72
5.2	Visual assessment of single-leg squat performance (II).....	73
5.2.1	Subjects	73
5.2.2	Correlation between visual assessment and 2D video analysis.....	74
5.2.3	Intra- and inter-rater reliability	75
5.3	Knee control and injury risk in young floorball and basketball players (III).....	75
5.3.1	Subjects	75
5.3.2	Lower extremity injury risk factors.....	76
5.3.3	Sensitivity and specificity analyses	78
5.3.4	Age, sex, and side-to-side differences	79
5.4	Knee control and injury risk in youth football players (IV).....	79
5.4.1	Subjects	79
5.4.2	Lower extremity injury risk factors.....	81
5.4.3	Non-contact lower extremity injury risk factors	83
5.4.4	Age, sex, and side-to-side differences in the FPKPA	83
6	DISCUSSION	85
6.1	Physical activity-related injuries as a public health issue.....	85
6.1.1	Injury prevalence in different settings.....	85
6.1.2	Physical activity promotion and injury prevention	86
6.1.3	Importance of surveillance and monitoring.....	87

6.1.4	Injury prevention.....	88
6.2	Single-leg squat as a tool to assess frontal plane knee control	88
6.2.1	Visual assessment of knee control.....	89
6.2.2	Intra- and inter-rater reliability.....	89
6.2.3	2D analysis of knee control in comparison to the 3D analysis	90
6.3	Reduced knee control as a lower extremity injury risk factor	91
6.3.1	Frontal plane knee control as a lower extremity injury risk factor	91
6.3.2	Improving knee control and physical performance	93
6.4	The 2D analysis of the single-leg squat as a screening test.....	94
6.4.1	The predictive value of FPKPA	94
6.4.2	The practical value of movement control tests.....	94
6.5	Age, sex, and side-to-side differences in frontal plane knee control.....	95
6.5.1	Leg dominance	96
6.5.2	Age and sex	97
6.6	Strengths and limitations	98
6.7	Future implications.....	100
7	CONCLUSIONS.....	101
	ACKNOWLEDGEMENTS.....	102
	REFERENCES	104
	ORIGINAL PUBLICATIONS.....	131

1 INTRODUCTION

Sports and physical activity (PA) are leading cause of adolescent injuries in many developed countries (Pickett et al., 2005). These injuries may lead to short-term disability and long-term health problems. There are economic and societal pressures on the field of sports medicine to develop and implement valid injury prevention strategies (Hewett, Myer, Ford, Paterno, & Quatman, 2016).

Fast-paced team sports are very popular among adolescents who participate in organised sports and/or leisure time PA. The most popular sports vary between countries; in Finland, football (soccer), floorball, ice hockey and basketball are among the most popular adolescent sports (Mononen, Blomqvist, Koski, & Kokko, 2016). These sports include frequent pivoting turns and quick accelerations and decelerations. In these sports, injury incidence is high and adolescents are injured more frequently than are adults (Pasanen et al., 2017, 2018; Stuart & Smith, 1995; Åman, Forssblad, & Henriksson-Larsén, 2016). It has been previously suggested that injury prevention efforts should target team-ball sports because of the high injury rates and the significant impacts on the injured participants (Finch & Cassell, 2006). In team-ball sports, most injuries affect the lower extremities (Agel et al., 2007; Clausen et al., 2014; Moller, Attermann, Myklebust, & Wedderkopp, 2012; Pasanen et al., 2008; Söderman, Adolphson, Lorentzon, & Alfredson, 2001). For these reasons, the focus of this doctoral dissertation is on lower extremity injuries in adolescent team-ball sports.

Given the need to reduce the burden caused by sports injuries, the ability to identify athletes with a higher risk of injury, who could then be targeted with suitable prevention strategies, is paramount. Hence, there is significant motivation to establish reliable screening tests with high specificity and sensitivity to identify athletes with an elevated risk of injury. While several potential screening tests have been studied, many are used without an understanding of their association with future injuries, such as the single-leg squat (SLS) test.

The frontal plane, also known as the coronal plane, is the plane of motion that divides the body into front and back sections (Hamill & Knutzen, 1995). Poor frontal plane knee control, which can manifest as extensive medial movement of the knee during athletic tasks, has been suggested as a risk factor for lower

extremity injuries (Hewett et al., 2005; Myer et al., 2010; O’Kane et al., 2015). The SLS is often used in clinical practice to assess frontal plane knee control. However, the associations between knee control during the SLS and the risk of future injuries has not been previously studied. The purpose of this doctoral thesis is to focus on this critical knowledge gap.

2 REVIEW OF LITERATURE

2.1 Adolescent sports injuries as a public health issue

Adolescence is defined as a period of transition from childhood to adulthood (World Health Organization, 1986). The World Health Organization considers the age of adolescence to be from 10 to 19 years. However, there is typically considerable variation in the onset and termination of adolescence (Malina, Bouchard, & Bar-Or, 2004). In their work on youth athletic development, Lloyd and Oliver (2012) define adolescence as a period from 12 to 21 years for boys and 10 to 20 years for girls. Since both sexes are studied in this thesis, adolescence is defined as extending from 10 to 21 years of age.

Participating in organised sports in adolescence is associated with a cluster of positive health behaviours, including a higher likelihood of meeting the recommendations for PA, screen time, and fruit and vegetable consumption (Vella, Cliff, Okely, Scully, & Morley, 2013). Being physically active confers many benefits in terms of mental and physical health (Janssen & LeBlanc, 2010) and wellbeing, and it promotes scholastic performance (Bangsbo et al., 2016; Haapala et al., 2017). Adolescent PA participation has also been shown to lead to higher socioeconomic status (Kari et al., 2016; Koivusilta, Nupponen, & Rimpelä, 2012) and an increased likelihood of PA participation in adulthood (Kjønniksen, Anderssen, & Wold, 2009; Perkins, Jacobs, Barber, & Eccles, 2004). As sedentary lifestyle has become a large-scale problem (Tremblay et al., 2011), PA promotion among adolescents is considered a key public health issue. However, the promotion of physical activity does include potentially adverse effects (Verhagen, Bolling, & Finch, 2015).

Sports participation is a major cause of adolescent injuries in developed countries (Bijur et al., 1995; Burt & Overpeck, 2001; Conn, Annet, & Gilchrist, 2003; Dekker, Kingma, Groothoff, Eisma, & Ten Duis, 2000; Finch, Mitchell, & Boufous, 2011; King, Pickett, & King, 1998; Leadbeater, Babul, Jansson, Scime, & Pike, 2010; Mattila, Parkkari, Kannus, & Rimpelä, 2004; Michaud, Renaud, & Narring, 2001; Schwebel & Brezaussek, 2014; Tiirikainen, Lounamaa, Paavola, Kumpula, & Parkkari, 2008). In Finland, sports participation is the leading cause of hospitalisation during adolescence (Mattila, Parkkari, Koivusilta, Kannus, &

Rimpelä, 2009). In addition to the short-term consequences of sports injuries, it is important to address the long-term outcomes. Sports injuries, especially knee injuries, can lead to a higher likelihood of overweight or obesity and reduced knee function (Whittaker, Woodhouse, Nettel-Aguirre, & Emery, 2015), as well as an increased risk of osteoarthritis later in life (Lohmander, Östenberg, Englund, & Roos, 2004) .

It has been reported in Australia that among adolescents and children, the population-health burden of sports injuries is greater than that incurred by road traffic injuries (Finch, Wong Shee, & Clapperton, 2014). While road traffic injury prevention is incorporated into the public health agendas, sports injuries are not commonly acknowledged in those agendas, despite the magnitude of the problem (Finch, 2012). Although sports injuries are often overlooked as a public health issue (Parkkari, Kujala, & Kannus, 2001), in Finland, the National Action Plan for Injury Prevention among Children and Youth does address the importance of preventing adolescent PA-related injuries (Markkula & Öörni, 2010).

As participation in organised sports has become increasingly popular (Carter & Micheli, 2011), there has been a concomitant increasing prevalence of sedentary lifestyle (Tremblay et al., 2011), and we are witnessing the polarisation of PA. As PA promotion efforts are directed towards the less active and it is established that adolescent sports injuries create significant population-health burden (Collard, Verhagen, van Mechelen, Heymans, & Chinapaw, 2011; de Loës, Dahlstedt, & Thomée, 2000; Knowles et al., 2007), the cost incurred by PA-related injuries and injury-related health problems represent a major issue. For example, in Australia, direct hospital costs during a 7-year period were used as one measure of the population-health burden of sports injuries among children aged under 15 years (Finch et al., 2014). Costs of sports injuries were found to be 2.6-fold the cost of road traffic injuries.

Injury prevention strategies can reduce the number of injuries and lead to cost - savings overall. Use of an injury prevention exercise program (IPEP) has been shown to reduce the health care cost of youth football injuries by 43% (Marshall, Lopatina, Lacny, & Emery, 2016). A study on adolescent ice hockey demonstrated significant cost-savings related to a policy disallowing body checking in 11- and 12-year-old males (Lacny et al., 2014).

2.2 Sports injury risk factors in adolescence

Sports injuries occur as a result of interactions between multiple risk factors, which can be divided into extrinsic and intrinsic risk factors (Taimela, Kujala, & Osterman, 1990). Extrinsic factors occur independently of the individual and are related to the particular sport: how the sport is practiced, the environment, and the equipment (Lysens et al., 1984; Taimela et al., 1990). Intrinsic risk factors are the physical and psychosocial characteristics of the individual (Lysens et al., 1984). Both the extrinsic and intrinsic factors can be further divided into modifiable and non-modifiable risk factors. Modifiable risk factors are those that could potentially be modified by injury prevention strategies, and they are also referred to as potentially modifiable risk factors (Emery, 2003).

2.2.1 Non-modifiable extrinsic risk factors

Non-modifiable extrinsic risk factors include the type of sport, level of play, position played, weather, and time of season (Emery, 2003). In team sports, the risk of getting injured is highly related to the characteristics of the team, even more than to the features of an individual player (Inklaar, Bol, Schmikli, & Mosterd, 1996). There is general agreement among sports injury researchers that the risk of injury is greater during competition than in training (Murphy, Connolly, & Beynnon, 2003).

There are discrepancies in the literature regarding the level of play as a risk factor among adolescents. While some studies have reported a higher risk of injury among the elite divisions compared to the lower divisions in certain age groups, this finding was not consistent among all of the studied age groups (Emery, Meeuwisse, & Hartmann, 2005; Emery & Meeuwisse, 2006). In football, the low-level youth players had a higher incidence of injuries compared to the high-level players in relation to exposure time (Peterson, Junge, Chomiak, Graf-Baumann, & Dvorak, 2000). This was hypothesised to be due to more training in the higher levels, which could enable the players to be more prepared to meet the requirements of the game.

2.2.2 Potentially modifiable extrinsic risk factors

The rules, coaching, training methods, and use of protective equipment are potentially modifiable extrinsic risk factors (Collard, Verhagen, Chin A Paw, & van Mechelen, 2008). Some environmental factors, like the playing surface, are also considered potentially modifiable.

Passive methods such as rule changes and the use of protective equipment have been shown to be very effective methods of injury prevention. For example, a change in rules to eliminate body checking in ice hockey among 11- and 12-year-olds led to reduced risk of overall injury and concussion (Black et al., 2016; Black, Hagel, Palacios-Derflinger, Schneider, & Emery, 2017). Moreover, the use of full or partial facial protection in junior ice hockey significantly reduced eye and face injuries compared to the players with no facial protection (Stuart, Smith, Malo-Ortiguera, Fischer, & Larson, 2002). In Finland, use of protective eyewear became mandatory in junior floorball after high rates of eye injuries were reported (Leivo, Puusaari, & Mäkitie, 2007). As a result, the incidence of floorball eye injuries has significantly declined (Leivo, Haavisto, & Sahraravand, 2015). Bicycle helmet use has been shown to significantly reduce the risk of head, brain, and facial injuries in all age groups (Thompson, Rivara, & Thompson, 1994).

Environmental aspects, such as the type and the condition of the playing surface are considered risk factors (Lysens et al., 1984), but there is very little research on this topic in adolescent sports. In female youth football, no differences in injury rates have been detected between grass and artificial grass (Häggglund & Waldén, 2015; Steffen, Andersen, & Bahr, 2007). In American football, playing on artificial turf has been associated with a higher injury rate (Ramirez M, Schaffer KB, Shen H, Kashani S, & Kraus JF, 2006).

The association between training load and the risk of injuries is complex. Most studies investigating the relationship between training load and injury risk have been done on adults (Drew & Finch, 2016). While higher training loads have been associated with higher injury rates in adults, high loads can also be protective against injury (Gabbett, 2016). In a study on adolescent rugby players, training injuries peaked early in the season (Gabbett, 2005). The highest training loads in midseason did not lead to an increase in training injuries. In elite youth handball, increases in the training load were associated with dominant arm shoulder injuries, and a greater than 60% increase in handball load was associated with a higher risk of shoulder injuries (Møller et al., 2017). A greater than 60% increase in handball load was associated with a higher risk of shoulder injuries. In volleyball, a high

training and competition load was associated with the risk of developing jumper's knee (Visnes & Bahr, 2013). The athletes who developed jumper's knee did approximately three more hours of volleyball training per week compared with the asymptomatic athletes. In elite youth football, both a high accumulated workload and a high acute workload were associated with a higher risk of sustaining a new injury (Bowen, Gross, Gimpel, & Li, 2017). Furthermore, in elite youth football, athletes with a history of low number of weekly training sessions had a higher incidence of groin injuries when they moved to a more intensive training program at a sports institute (Lovell, Galloway, Hopkins, & Harvey, 2006). In elite male youth football players, training load, as well as other measures of physical stress, including strain, weekly duration and monotony, were associated with the risk of injury (Brink et al., 2010). In adolescent female football, higher self-reported same day and previous day training loads were associated with the risk of injury (Watson, Brickson, Brooks, & Dunn, 2017). The ratio between acute and chronic training load was a significant predictor of injury. In addition to high training loads, low loads also seem to increase the injury risk. In adolescent female football players, players participating once a week or less were 3 to 10 times more likely to sustain a time-loss injury than were other players (Clausen et al., 2014). Among adolescents, it seems that both low and high exposure can increase the risk of injuries, as is suggested to be the case in adults (Gabbett, 2016). In general, very low exposure and significant increases in load should be avoided.

Early specialisation in one sport has become more common in recent years and retrospective studies have suggested that it may be associated with the risk of injuries (Bell et al., 2016; Jayanthi, LaBella, Fischer, Pasulka, & Dugas, 2015; Post, Bell, et al., 2017; Post, Trigsted, et al., 2017). A recent prospective study among high school athletes reported that athletes with a moderate or high level of primary sport specialisation showed a higher risk of injury compared to athletes with a low level of specialisation (McGuine et al., 2017). Similarly, a study on National Basketball Association players reported that athletes who participated in other sports in addition to basketball in high school had fewer major injuries and longer careers than did players who only played basketball (Rugg, Kadoor, Feeley, & Pandya, 2018).

2.2.3 Non-modifiable intrinsic risk factors

Non-modifiable intrinsic risk factors include age, sex, and previous injuries. Previous injury is the most well-established risk factor for sustaining a sports injury (Toohey, Drew, Cook, Finch, & Gaida, 2017; Witchalls, Blanch, Waddington, & Adams, 2012). Previous injury not only increases the risk of a subsequent injury to the same body part but also increases the risk of a range of subsequent lower extremity injuries (Toohey et al., 2017).

Generally, injury rates increase with age (Spinks & McClure, 2007). When analysing the period of adolescence, adolescents over the age of 13 years have a higher risk of injury compared to younger adolescents and children (Emery, 2003). The higher rate of injuries among older adolescents is related to their increased body mass, longer joint lever arms, and the ability to generate more power compared to prepubescent athletes (Fort-Vanmeerhaeghe et al., 2016). The increase in injuries with age is more prevalent among boys than among girls (Caine, Maffulli, & Caine, 2008). This is possibly because the gains in power and strength related to growth in girls are smaller than those in boys (Beunen & Malina, 1988).

In general, males have a higher risk of adolescent sport injuries than girls (Emery, 2003). However, before puberty the injury rates are similar between the sexes, and differences in injury risk between sexes can be sport-specific. In youth football, previous studies have reported no significant sex differences in injury risk (Emery et al., 2005; Faude, Rößler, & Junge, 2013; Kucera, Marshall, Kirkendall, Marchak, & Garrett Jr, 2005). Even though the injury incidence is somewhat similar between adolescent boys and girls, there are sex differences when it comes to injuries in specific body parts and injury types. Previous studies have reported no difference in overall injury incidence between sexes in basketball (Messina, Farney, & DeLee, 1999; Pasanen et al., 2017; Yde & Nielsen, 1990), though significant differences were detected in terms of in lower extremity injuries: there was a higher rate of injuries among girls than among boys (Messina et al., 1999). A higher risk of first-time ankle sprain among female high school basketball players compared to male players has been reported (Beynnon, Vacek, Murphy, Alosa, & Paller, 2005). In volleyball, males had a higher risk of developing jumper's knee than females (Visnes & Bahr, 2013). Girls are reported to sustain more knee injuries in basketball and football compared to boys (Powell & Barber-Foss, 2000). Generally, girls are considered to have a higher risk of anterior cruciate ligament (ACL) injury (Agel, Arendt, & Bershadsky, 2005; Arendt & Dick, 1995; Shea,

Pfeiffer, Wang, Curtin, & Apel, 2004; Waldén, Hägglund, Werner, & Ekstrand, 2011).

Growth and maturation are relevant non-modifiable intrinsic factors, but their relationship with injury risk remains unclear. Growth and maturation are not interchangeable. Growth refers to the quantifiable change in body size, while maturation refers to structural and functional changes in the organism's progress toward a fully mature state (Read, Oliver, De Ste Croix, Myer, & Lloyd, 2015). An adolescent growth spurt is the period of maximal gain of stature and weight during the pubertal period. In a study of elite youth football players (aged 11 to 19 years), a gain in stature of ≥ 0.6 cm per month and ≥ 0.3 kg/m² increase in body mass index (BMI) value per month were both associated with a higher risk of injury (Kemper et al., 2015). Years from peak height velocity (PHV) is a non-invasive maturity assessment that is based on the differential timings of growth of height, sitting height, and leg length (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). A study on the risk of injuries in different phases of the adolescent growth spurt in a small group (n=26) of talented male youth football players reported that the number of acute injuries was higher in the PHV year than in the year prior (van der Sluis et al., 2014). Among academy male football players, early maturation and higher training and match exposure together were associated with an increased injury incidence (Johnson, Doherty, & Freemont, 2009). However, Le Gall and colleagues (2007) detected no significant differences in injury incidence between early, normal, and late maturing male football players. Menarche is also considered a sign of maturation. In female youth ice hockey, menarche was identified as a risk factor among 11- to 12-year-olds, with players who had begun menstruating at preseason showing a higher risk of injury (Decloe, Meeuwisse, Hagel, & Emery, 2014).

Family history is a non-modifiable risk factor. In active adolescent females, family history of osteoporosis or osteopenia was associated with the risk of stress fracture (Loud, Micheli, Bristol, Austin, & Gordon, 2007). In adolescent female football, family history of ACL injury was associated with the risk of ACL injury and acute knee injury (Hägglund & Waldén, 2015).

2.2.4 Potentially modifiable intrinsic risk factors

Potentially modifiable intrinsic risk factors are body composition (Collard et al., 2008), fitness level, training, strength, flexibility, joint stability, biomechanics, balance, and psychological and social factors (Emery, 2003).

Heavier athletes need to absorb greater forces through soft tissue and joints, which may be why athletes are more susceptible to injury in some sports (Emery, 2003). In American football, while higher BMI has been associated with an elevated risk of ankle sprains (Gribble et al., 2015; McHugh, Tyler, Tetro, Mullaney, & Nicholas, 2006; Tyler, McHugh, Mirabella, Mullaney, & Nicholas, 2006), no association with the overall injury rate has been detected (Malina et al., 2006; Ramirez M et al., 2006; Turbeville, Cowan, Asal, Owen, & Anderson, 2003; Turbeville, Cowan, Owen, Asal, & Anderson, 2003). One proposed mechanism by which high BMI increases the risk of ankle sprain injury is the inability to control momentum during changes in direction (McHugh, 2010). When investigating only the linemen, a higher incidence of lower extremity injuries was noticed among athletes with a high BMI and high body fat percentage (Gomez et al., 1998). No association between BMI and injury risk was demonstrated in basketball (McGuine, Greene, Best, & Levenson, 2000; McGuine & Keene, 2006) or football (Emery et al., 2005; McGuine & Keene, 2006). In volleyball, neither height, weight, body fat percentage, or waist circumference was associated with the risk of developing jumper's knee (Visnes & Bahr, 2013). In basketball, volleyball, and football the variation in body size in a team of adolescent athletes is smaller than that in American football, in which some playing positions require increased body size. Body fat percentage as an injury risk factor in adolescent sports has not been extensively studied. Kemper and colleagues (2015) reported that a low body fat percentage was an injury risk factor among elite male youth football players. A body fat percentage <7% for males aged 11 to 16 years and <5% for males aged 16 to 19 years was associated with a higher risk of injury.

An individual athlete's skill level can also be associated with the risk of injuries. In female youth football, the more skilled players were at a greater risk of injury than were the players with a low skill level (Soligard, Grindem, Bahr, & Andersen, 2010). This was consistent with a similar finding in young male football players: the players with a higher skill level, according to the coach's assessment, had a higher risk of injuries compared to the less skilled players (Schwebel, Banaszek, & McDaniel, 2007).

Psychosocial variables can affect the risk of injuries. A stress-injury relationship has been identified in high school football: athletes with more negative life changes had a higher risk of sustaining an injury (Gunnore, Horodyski, Tennant, & Murphey, 2001). Moreover, perfectionism has been associated with an increased risk of injury in junior athletes (Madigan, Stoeber, Forsdyke, Dayson, & Passfield, 2018). However, when investigating the association between psychological factors assessed by the coach and the risk of football injuries, inhibition, aggression, and risk-taking were not associated with the risk of injury (Schwebel et al., 2007).

Strength measures have been associated with injuries in adolescents. Low levels of hip muscle (De Ridder, Witvrouw, Dolphens, Roosen, & Van Ginckel, 2016; Leetun, Ireland, Willson, Ballantyne, & Davis, 2004; O’Kane et al., 2017; Verrelst et al., 2014), hamstring, and quadriceps strength (O’Kane et al., 2017) have been associated with an elevated injury risk.

Joint laxity can contribute to injury risk, but the research on adolescent athletes is limited. In male collegiate athletes, tight ligaments have been associated with a higher risk of ankle injury (Krivickas & Feinberg, 1996). In young female athletes, knee hyperextension beyond normal has been associated with an elevated ACL injury risk (Myer, Ford, Paterno, Nick, & Hewett, 2008).

Deficits in dynamic stability can be witnessed as higher postural sway or instability. Poor single leg balance has been associated with a higher risk of ankle injuries in adolescent athletes (McGuine et al., 2000; Trojian & McKeag, 2006; Wang, Chen, Shiang, Jan, & Lin, 2006).

Neuromuscular imbalances are muscle strength or muscle activation patterns that lead to increased joint load (Myer, Ford, & Hewett, 2004). Neuromuscular imbalances, like quadriceps dominance, leg dominance, poor frontal plane knee control (ligament dominance), and core dysfunction (trunk dominance) have been associated with higher injury risk (Fort-Vanmeerhaeghe et al., 2016; Myer, Brent, Ford, & Hewett, 2011; Read, Oliver, De Ste Croix, Myer, & Lloyd, 2016). Quadriceps dominance refers to an imbalance in quadriceps and hamstring muscle activation patterns (Myer et al., 2004). Quadriceps dominant athletes rely on their knee extensors over knee flexors, which can manifest as landing with low knee flexion angles. In female collegiate athletes, a low hamstring-to-quadriceps ratio was associated with an elevated risk of overuse knee injuries (Devan, Pescatello, Faghri, & Anderson, 2004). Landing with a low knee flexion angle has been associated with an elevated risk of ACL injuries in young female athletes (Leppänen et al., 2017). Leg dominance refers to a side-to-side imbalance in lower extremity kinematics and muscular strength (Myer et al., 2004). Leg dominance has

been reported to be a risk factor for lower extremity injury (Read, Oliver, De Ste Croix, Myer, & Lloyd, 2018) and overall injury (Knapik, Bauman, Jones, Harris, & Vaughan, 1991). Trunk dominance is described as an imbalance between the inertial demands on the trunk and the ability of the core muscles to control for the excessive trunk motion (Myer, Brent, et al., 2011). Both the frontal plane and sagittal plane trunk motions can impact lower extremity alignment and affect the risk of injuries (Powers, 2010). Deficits in trunk control that lead to trunk displacement have been associated with an increased risk of knee, ligament, and ACL injuries in collegiate female athletes (Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). According to a recent meta-analysis, poor core stability is a risk factor for lower extremity injuries (De Blaiser et al., 2018).

Frontal plane knee control as a risk factor will be described in detail in the next chapter (2.3).

2.3 Knee valgus and frontal plane knee control

2.3.1 Frontal plane knee control

Poor frontal plane knee control refers to insufficient control of the medio-lateral knee motions. This neuromuscular deficit, also referred to as ligament dominance, can be displayed as excessive knee valgus and high ground reaction forces during athletic tasks (Ford, Myer, & Hewett, 2003; Hewett, Paterno, & Myer, 2002; Myer et al., 2004). Valgus refers to the outward angulation of a body segment from its proximal end to its distal end (Kreighbaum & Barthels, 1985). In the knee joint, valgus can be observed as medial positioning of the knee compared to the neutral lower extremity alignment (Figure 1). Knee valgus is often observed on the frontal plane but it can be a multi-planar motion. Knee valgus can result from femoral adduction or the combination of femoral adduction and tibial abduction (Powers, 2003). Tibial abduction can result from ankle pronation or be an accommodation to femoral adduction. In addition, internal and external rotations of the femur and/or tibia can be present (Quatman, Quatman-Yates, & Hewett, 2010). Femoral adduction can result from poor hip abductor strength, such as weak gluteus medius (Powers, 2003).



Figure 1. Representation of knee valgus in a single-leg stance (left) and double-leg stance (right).
Figure created with Kineman Pro.

2.3.2 Factors contributing to frontal plane knee control

Reduced hip muscle strength is associated with greater knee valgus angles during athletic tasks (Claiborne, Armstrong, Gandhi, & Pincivero, 2006; Hollman et al., 2009; Willson, Ireland, & Davis, 2006). Several studies have established that hip abductors play an important role in controlling frontal plane knee motion (Claiborne et al., 2006; Crossley, Zhang, Schache, Bryant, & Cowan, 2011; DiMattia, Livengood, Uhl, Mattacola, & Malone, 2005; Stickler, Finley, & Gulgin, 2015). In addition, hip external rotation strength has been associated with frontal plane knee control in females (Willson et al., 2006) and hip extensor strength seems to be an important contributor to frontal plane control during landing tasks (Pollard, Sigward, & Powers, 2010). Not only muscle strength, but also the neuromuscular recruitment of hip muscles seems to contribute to maintenance of neutral lower extremity alignment. Hollman and colleagues (2009) concluded that among females, neuromuscular recruitment of the gluteus maximus is even more

important than muscle strength. This is supported by the work of Mizner and colleagues (2008), who demonstrated that collegiate female athletes can improve knee control in a single training session, when they are instructed as to technique. This improvement was not predicted by hip muscle strength, and it is likely that neuromuscular factors, such as muscle activation patterns, influence how well an athlete can control the lower extremity alignment (Mizner et al., 2008; Powers, 2010). In addition to muscle strength and neuromuscular activation, other lower extremity functions can contribute to frontal plane knee motions. Limited ankle dorsiflexion range of motion (ROM) can contribute to knee valgus (Lima et al., 2018). For example, when knee flexion is increased, such as during a squat, increased ankle dorsiflexion is needed to allow the tibia to move forward. If ankle dorsiflexion is limited, perhaps due to decreased extensibility of the gastrocnemius/soleus complex, subjects might try to compensate for this by moving the knee medially towards valgus (Dill, Begalle, Frank, Zinder, & Padua, 2014; Lima et al., 2018).

Previous studies suggest that there are sex differences in frontal plane knee control, as female athletes demonstrate greater valgus angles than do males. Greater frontal plane knee motion in females compared to males has been reported in running (Ferber, Davis, & Williams, 2003), landing (Ford et al., 2003; Holden, Boreham, & Delahunt, 2016; Jacobs, Uhl, Mattacola, Shapiro, & Rayens, 2007) and the SLS (Baldon et al., 2011; Willson et al., 2006). However, Claiborne and colleagues (2006) did not detect significant differences in frontal plane knee kinematics during the SLS between sexes. Previous studies have reported differences in muscle activation between males and females. It has been suggested that females depend on the abductor muscles (Baldon et al., 2011) and also utilise the rectus femoris (Dwyer, Boudreau, Mattacola, Uhl, & Lattemann, 2010; Zazulak et al., 2005; Zeller, McCrory, Kibler, & Uhl, 2003) more than males to control knee motions. A meta-analysis on sex differences in landing biomechanics in adolescents reported that the difference in knee control between male and female athletes increase with age (Holden et al., 2016).

2.3.3 Frontal plane knee control and injuries

Knee valgus can be harmful, since it alters the loads experienced by different tissues in the lower extremities. If the ability to control trunk, hip, and knee motions during athletic tasks is poor, the athlete can allow the ground reaction

forces to control the lower extremity alignment (Hewett et al., 2002). This may lead to high loads on the knee ligaments and be a mechanism that contributes to ACL injuries (Myer et al., 2004). Poor frontal plane knee control has also been associated with the development of patella-femoral pain syndrome (PFPS) (Holden, Boreham, Doherty, & Delahunt, 2017; Myer et al., 2010). When the knee is loaded in a valgus angle, the lateral forces acting on the patella-femoral joint increase, which may contribute to the development of PFPS (Powers, 2010). Knee valgus is also considered a potential risk factor for iliotibial band syndrome, the proposed mechanism for which is that the hip adduction causes an increase in the strain to the iliotibial band (Powers, 2010), especially when coupled with knee internal rotation (Ferber, Noehren, Hamill, & Davis, 2010). In a study on recreational female runners, excessive hip adduction and knee internal rotation during the stance phase of running predicted iliotibial band syndrome (Noehren, Davis, & Hamill, 2007).

The premise that extensive knee valgus is related to the risk of lower extremity injuries is based on the finding that valgus collapse is often observed in the context of ACL injury (Krosshaug et al., 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004). Valgus collapse is described as a combination of knee valgus, hip internal rotation, and tibial rotation (Quatman & Hewett, 2009). Since valgus collapse is often observed in ACL injuries, it is hypothesised that perhaps the presence of knee valgus during athletic tasks is associated with an elevated risk of lower extremity injuries. This hypothesis has served as the basis of studies seeking to determine the association between variables of knee control during movement control test and the risk of lower extremity injuries. Previous studies on adolescent female athletes have detected associations between increased knee abduction moment and ACL injuries (Hewett et al., 2005) and patella-femoral pain (Myer et al., 2010), high knee valgus displacement and patella-femoral pain (Holden et al., 2017), and low normalised knee separation and lower extremity and knee injuries (O’Kane et al., 2015). However, a recent study did not detect significant associations between knee valgus angle or knee abduction moment and ACL injuries (Leppänen et al., 2017).

2.4 Screening tools to predict lower extremity injuries in adolescent athletes

2.4.1 Screening as a concept

It is important to identify modifiable and non-modifiable sports injury risk factors and the concept of screening takes this goal one step further. The aim is to establish which tests can be used to screen for an elevated risk of future injuries. In medicine, screening is used to identify asymptomatic individuals with a disease. In Finland, population level screening tests are utilised to screen for breast cancer, cervical cancer, and colon cancer. The result of a screening test is dichotomous (yes/no): there are cancerous or precancerous cells or there are not. However, in sports injury research the attempt is not to screen for signs of injury but for a high-risk status (Myer, Brent, et al., 2011), which means screening for potentially modifiable intrinsic factors that are associated with the risk of injury, such as faulty movement patterns, inadequate strength levels, or joint hyper- or hypomobility. Therefore, the concept of sports injury screening differs from that of asymptomatic disease screening.

Guidelines for screening program evaluation are often based on the Willson-Jungner criteria (Wilson & Jungner, 1968). For a screening test to be reliable, it must provide enough true positives and true negatives and not too many false positives or false negatives. In addition, there needs to be a treatment or a cure for the condition.

When evaluating the potential of a screening test to predict sports injuries, sensitivity, specificity, positive predictive value, and negative predictive value are usually assessed (Table 1). Sensitivity refers to the proportion of at-risk subjects who are correctly identified (Glover & Albers, 2007). Specificity refers to the proportion of subjects who are correctly identified as being not at-risk. Positive predictive value indicates what proportion of subjects who are identified as at-risk can be correctly categorised. Negative predictive value expresses the proportion of those identified as not at-risk, that can be correctly identified. When sensitivity is high, the results include only a few false negatives. When specificity is high, only a few false positives are included in the results. High specificity is important for correct positive detection of conditions that require an intervention but are not fatal, such as many sports injury risk factors. A clinical test with moderate to high specificity is useful to rule in a disorder when the results are positive (DiMattia et

al., 2005). High sensitivity is crucial for identifying a large proportion of the athletes who are most likely to be injured (Wilkerson, Giles, & Seibel, 2012). On the other hand, high specificity is valuable for the organisation to avoid wasting resources on players who have a lower risk of becoming injured. The relationship between the true status and screening test results is presented in Figure 2. The values in the fourfold table can be used to calculate the sensitivity, specificity, positive predictive value, and negative predictive value (Portney & Watkins, 2009).

Screening test result		True status	
		Disorder	No disorder
Positive test result		True positive	False positive
		False negative	True negative

Figure 2. The relationship between screening test results and true status of a disorder. Adapted from Portney & Watkins (2009).

Athletic trainers, physiotherapists and physicians utilise movement assessments in clinical work with the intent to identify high-risk athletes. It is hypothesised that based on the results of the screening, the training program could be tailored to the individual athlete in order to prevent injuries (Myer, Brent, et al., 2011). Over the past few decades there has been considerable interest in research on screening tests. In a recent systematic review, Dallinga and colleagues (2012) identified screening tools to predict injuries in team sports, but most of the studies were done on adults. In addition the reliability and predictive value of movement screenings were recently assessed in a critical review (McCunn, aus der Fünter, Fullagar, McKeown, & Meyer, 2016). The following chapters will summarise the findings of prospective studies exploring the associations between a screening test score and the risk of lower extremity injury in adolescent team sport athletes. Studies on collegiate students are included even though not all subjects are considered adolescents.

Table 1. Considerations and questions for evaluating sports injury risk screening methods – adapted from Bahr (2016a), Fox et al. (2016), Glover and Alberts (2007), and Wilson and Jungner (1968)

Consideration	Question
Appropriateness for the intended use	
Association with injury risk	Are the measured variables relevant for determining individual risk status?
Theoretical and empirical support	Has the procedure of the screening method been validated in previous research? Is there a predetermined cut-off value for the test from a previous prospective cohort study?
Population fit	Is the screening method appropriate for the population of interest?
Technical adequacy	
Test-retest/intra-rater reliability	Are the results of the screening method consistent over time?
Inter-rater reliability	Are the results of the screening method consistent across raters?
Predictive validity	
Sensitivity	Does the test capture all those with an injury?
Specificity	Does the test capture only those with an injury?
Positive predictive value	What proportion of athletes with a positive test are injured?
Negative predictive value	What proportion of athletes with a negative test are injured?
Usability	
Balance of cost and benefit	Are the costs of the screening method reasonable? Does screening lead to savings on injury-related costs?
Feasibility of implementation	Are the personnel able to administer the screening method?
Utility of outcomes	Can athletes and coaches understand the implications of the screening method outcomes? Are the outcomes useful? Is there an intervention programme that has been validated in a randomised controlled trial?

2.4.2 Star excursion balance test

The star excursion balance test (SEBT) is a dynamic balance test in which the subject stands on one foot and uses the non-weight-bearing leg to perform maximal reach. Originally, the test included eight reaching directions. Later, after significant correlations between the reaching directions were detected, it was

concluded that only three reaching directions (anterior, posteromedial, and posterolateral) are needed (Gribble, Hertel, & Plisky, 2012). In addition, there is also another simplified SEBT protocol in use, utilising the anteromedial, medial, and posteromedial reaching directions (Hertel, Braham, Hale, & Olmsted-kramer, 2006; Steffen et al., 2017).

Previous studies on collegiate athletes have detected significant associations between SEBT scores and lower extremity injuries. In collegiate athletes, anterior asymmetry ≥ 4 cm was associated with a higher risk of non-contact injury (C. A. Smith, Chimera, & Warren, 2015). Among high school and collegiate American football players, the SEBT-anterior score normalised to leg length was associated with a higher risk of lateral ankle sprain (Gribble et al., 2015).

In high school basketball players, displaying an anterior side-to-side reach distance difference ≥ 4 cm or having a sum of the three directions that was $\leq 94\%$ of leg length was associated with an elevated risk of lower extremity injuries (Plisky, Rauh, Kaminski, & Underwood, 2006). Studies reporting significant associations between SEBT scores and injuries are presented in Table 2.

2.4.3 Vertical drop jump

The vertical drop jump (VDJ) is commonly used to analyse lower extremity kinetics and kinematics during landing. Among adolescent athletes, both three-dimensional (3D) and two-dimensional (2D) analyses of the VDJ have been utilised.

A study by Hewett and colleagues (2005) on the 3D analysis of the VDJ among female high school athletes is considered the first to report an association between knee valgus and a higher risk of ACL injuries. The study demonstrated that greater knee valgus and abduction load were significant risk factors for ACL injury. The subjects suffering an ACL injury during the follow-up demonstrated 2.5-times greater knee abduction moment and 20% higher ground reaction force during the VDJ than the uninjured subjects. In a recent study on female youth basketball and floorball players, Leppänen and colleagues (2017) reported significant associations between greater peak knee flexion angle and higher peak vertical ground reaction force and the risk of ACL injury. Knee valgus angle, peak knee abduction moment, knee flexion at initial contact, and medial knee displacement were not significantly associated with the risk of ACL injuries. Receiver operator characteristics (ROC) curve analysis indicated failed sensitivity and specificity for the peak knee flexion

angle and fair sensitivity and specificity for the vertical ground reaction force. In a study on young female basketball players, the athletes who developed patella-femoral pain during the follow-up demonstrated greater knee abduction moments in the pre-season VDJ compared to the healthy controls (Myer et al., 2010).

Using the 2D analysis of the VDJ in a study on female high school athletes, knee valgus displacement $\geq 10.6^\circ$ predicted patella-femoral pain (Holden et al., 2017) with a sensitivity of 0.75 and specificity of 0.85. The 2D analysis has also been utilised among adolescent female football players (O’Kane et al., 2015, 2017). For the post-menarchal players only, low normalised knee separation was associated with a higher risk of acute lower extremity injuries and knee injuries (O’Kane et al., 2015) and lower extremity overuse injuries and knee overuse injuries (O’Kane et al., 2017). However, the sensitivity and specificity were not determined in those two studies.

The Landing Error Scoring System (LESS) is a field-assessment tool used to identify potential high-risk movement patterns during the VDJ (Padua et al., 2009). To yield the LESS score, errors during the VDJ are calculated. There are 17 scored items in the LESS, and a lower score indicates fewer movement errors. In a study on high school and collegiate athletes, there was no association between the LESS score and the risk of ACL injuries in the entire cohort or the subgroups of collegiate athletes, high school athletes, males, or females (H. C. Smith et al., 2012). In elite youth football, the uninjured participants had lower (better) pre-season LESS scores than those sustaining an ACL injury during the follow-up (Padua et al., 2015). Based on the ROC curve analysis, a score of 5 was the optimal cut off point, generating a sensitivity of 86% and a specificity of 64%. The contrasting results of the two studies can be partly linked to the different ages of the subjects, in that the subjects in the study by Smith and colleagues were older compared to the subjects of Padua and colleagues. There is a natural decline in the LESS score with age; therefore, the LESS might have a limited ability to predict injuries among older adolescents. Studies reporting significant associations between VDJ performance and injuries are presented in Table 3.

2.4.4 Functional movement screen

The functional movement screen (FMS™) consists of seven fundamental movements that are scored on a scale of 0 to 3, with 3 being the best score for and individual test and 21 being the best composite score. The seven movements are

the deep squat, in-line lunge, hurdle step, shoulder mobility, active straight leg raise, trunk stability push-up, and quadruped rotary stability (Teyhen et al., 2012). A recent meta-analysis found the inter-rater and intra-rater reliability of the FMS™ to be excellent (Bonazza, Smuin, Onks, Silvis, & Dhawan, 2017).

Several studies have explored the association between an FMS™ composite score of 14 or less and the risk of injury. This cut-off value was detected by Kiesel and colleagues (2007) in their study on professional American football players. Among adolescent athletes, the results have been inconsistent. Three studies on collegiate athletes have investigated the FMS™ composite score of 14 or less but found no significant associations with injury risk (Chorba, Chorba, Bouillon, Overmyer, & Landis, 2010; Mokha, Sprague, & Gatens, 2016; Warren, Smith, & Chimera, 2015). In addition, an FMS™ composite score ≤ 14 was not associated with injury risk in male ice hockey players (Dossa, Cashman, Howitt, West, & Murray, 2014) or Australian football players (Chalmers et al., 2017). However, the combination of an FMS™ score ≤ 14 and self-reported past injury was associated with a higher risk of injury in collegiate athletes (Garrison, Westrick, Johnson, & Benenson, 2015).

Side-to-side asymmetry was associated with a higher risk of injury in Australian football players (Chalmers et al., 2017) but the finding was not repeated in the replication study (Chalmers et al., 2018). In collegiate football, volleyball, and rowing athletes, side-to-side asymmetry or a score of 1 in an individual test were both associated with a higher risk of musculoskeletal injury (Mokha et al., 2016).

The modified FMS™ was used to study the risk of lateral ankle sprains among high school and collegiate American football players (Gribble et al., 2015). Based on their pilot study, the researchers left out the push-up test, the shoulder mobility test and the trunk stability test. The modified FMS™, including the in-line lunge, deep squat, hurdle step, and straight-leg raise, was not associated with the risk of lateral ankle sprains.

While the FMS™ composite score does not seem to predict injuries among adolescent athletes, it should be kept in mind that the FMS™ may provide valuable information on side-to-side asymmetries and movement deficits. Studies reporting significant associations between FMS™ scores and injuries are presented in Table 4.

2.4.5 Strength measures

Some lower extremity strength measurements have been explored to study the association between strength and the risk of injury. In adolescent male football players, reduced hip extension strength, adjusted to body size, was associated with a higher risk of sustaining a lateral ankle sprain (De Ridder et al., 2016). Hip abduction, adduction, flexion, external rotation, and internal rotation strength have not been associated with the risk of ankle injuries (De Ridder et al., 2016; McHugh et al., 2006). In addition, no association was detected between the isokinetic ankle strength measures and the risk of ankle injuries in high school basketball players (Wang et al., 2006).

Among young female football players, greater hamstring, quadriceps, hip flexor, and hip external rotation strength measures were associated with a lower risk of knee overuse injury (O’Kane et al., 2017). Sensitivity and specificity were not evaluated.

Four core stability measures (hip abduction, hip external rotation, side bridge, back extension) were used in a study on collegiate basketball and track athletes (Leetun et al., 2004). Greater hip external rotation strength at baseline was significantly associated with a lower risk of sustaining a back or lower extremity injury. Sensitivity and specificity were not evaluated. Studies reporting significant associations between strength measures and injuries are presented in Table 5.

2.4.6 Predictive value of screening tests

As the information presented in Tables 2–5 demonstrates, there are several studies on adolescent athletes reporting significant associations between a screening test outcome and the risk of injuries, all of which provide valuable information on sports injury risk factors. However, it must be kept in mind that association does not equal prediction. Some studies attempted to validate previous cut-offs on different cohorts with mostly inconclusive results, as is the case with the FMS™. It must be taken into account that several studies in Tables 2–5 did not set out to study the predictive value of the test and therefore the sensitivity and specificity values are not available.

As mentioned previously, for a screening tool to be useful, it should have high sensitivity and specificity and low negative and high positive predictive value. However, thus far, most studies on screening tests show significant overlap between the injured and uninjured athletes (Bahr, 2016a). This is demonstrated by

the data of Chalmers and colleagues (2017) presented in Figure 3. No matter where the cut-off line is drawn, the test fails to create two distinctively different groups.

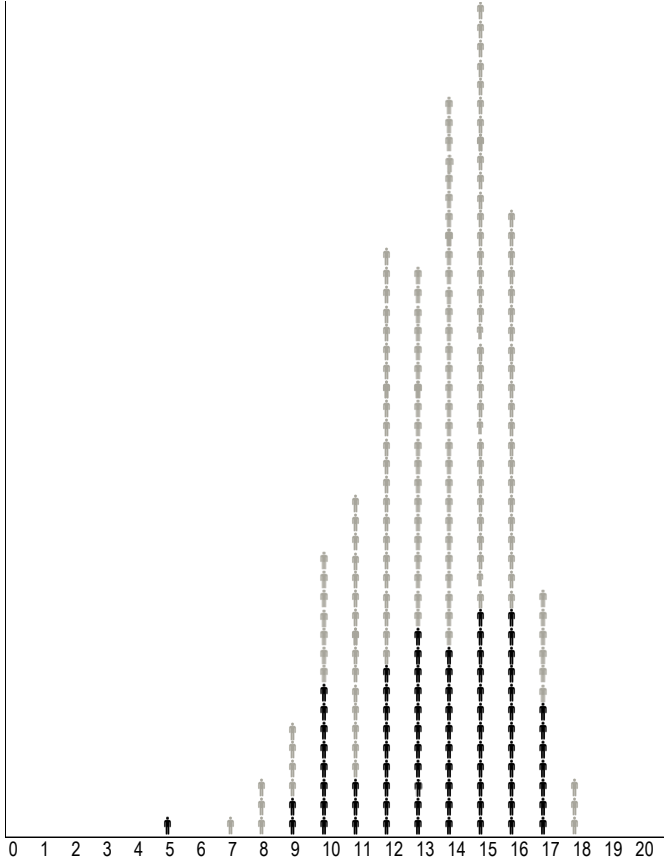


Figure 3. Representation of the data from Chalmers et al. (2017) illustrates the association between FMS composite score and lower extremity injury. Uninjured athletes are shown in grey, and athletes who suffered a lower extremity injury are shown in black.

Table 2. Characteristics of studies reporting significant associations between star excursion balance test (SEBT) results and the risk of injuries

Study	Outcome measures	Sport	Subjects	Injuries	Significant risk factors	Sensitivity and specificity
Gribble et al. 2015	• Reach distance normalised (%) to leg length (A, PM, PL, composite)	American football (high school, collegiate)	539 subjects (injured 17.3±2.3 years, uninjured 17.3±2.3 years)	Lateral ankle sprain	Normalised anterior reach distance (OR 2.84, 95% CI: 1.58 to 5.10, P<0.001)	For the normalised anterior reach distance: AUC 0.674. For the cut-off point of 67.2% of leg length: positive likelihood ratio 1.64
Plisky et al. 2006	• Mean reach distance (cm) right/left (A, PM, PL, composite) • Reach distance normalised (%) to leg length (A, PM, PL, composite) • Side-to-side difference in reach distance (cm) (A, PM, PL)	Basketball (high school)	130 M, 105 F (grades 9 to 12)	Lower extremity	• Anterior reach distance difference ≥4 cm (all players: OR 2.7, 95%CI: 1.4-5.3; M: OR 3.0, 95%CI: 1.1-7.7) • Normalised composite right leg reach distance ≤94.0% (all players: OR 3.0, 95% CI: 1.5 to 6.1; F: OR 6.5, 95% CI: 2.4 to 17.5)	ROC curve analysis performed to determine cut-off values. For girls: normalised composite right reach distance, 65.5% of uninjured subjects and 25% of injured subjects were below the cut-off. Other sensitivity and specificity values were not reported.
Smith et al. 2015	• Side-to-side difference in reach distance (cm) (A, PM, PL) • Normalised composite score (%)	Variety of collegiate sports	184 athletes (injured 20.6±1.6 years, uninjured 20.0±1.4 years)	Non-contact musculoskeletal	Side-to-side difference in anterior reach distance ≥4 cm (OR 2.20, 95% CI: 1.09 to 4.46, P=0.03)	Sensitivity 59%, specificity 72%

A=anterior, PM=posteromedial, PL=posterolateral, M=male, F=female, OR=odds ratio, AUC=area under the curve, ROC=receiver operating characteristics

Table 3. Characteristics of studies reporting significant associations between vertical drop jump (VDJ) performance and the risk of injuries

Study	Outcome measures	Sport	Subject characteristics	Injuries studied	Significant risk factors	Sensitivity and specificity
Hewett et al. 2005	<ul style="list-style-type: none"> • Knee abduction angle (°) (at IC and maximum) • Knee flexion angle (°) (at IC and maximum) • Peak knee flexion and abduction moments (Nm) • Peak hip adduction and flexion moments (Nm) • Peak vertical ground reaction force (N) 	Football, basketball, volleyball	205 F (injured 15.8±1.0 years, uninjured 16.1±1.7 years)	ACL	<ul style="list-style-type: none"> • Greater knee abduction moment (P<0.001) • Greater knee abduction angle (IC and peak) (P<0.001) 	For knee abduction moment: sensitivity 78%, specificity 73%
Holden et al. 2017	<ul style="list-style-type: none"> • Knee valgus displacement (°) 	Variety of sports	76 F (12.9±0.4 years)	Patella-femoral pain	Knee valgus displacement ≥10.6° (P<0.002)	For knee valgus displacement ≥10.6°: sensitivity 0.75, specificity 0.85, associated positive likelihood ratio 5
Leppänen et al. 2017	<ul style="list-style-type: none"> • Knee valgus and knee flexion angle at IC (°) • Peak knee abduction moment (Nm) • Peak knee flexion angle (°) • Peak vertical ground reaction force (N) • Medial knee displacement (mm) 	Basketball, floorball	171 F (15.4±1.9 years)	ACL	<ul style="list-style-type: none"> • Low peak knee flexion angle (HR for each 10° increase 0.55, 95% CI: 0.34 to 0.88, P=0.01) • High peak vertical ground reaction force (HR for each 100-N increase 1.26, 95% CI: 1.09 to 1.45, P<0.01) 	For peak knee flexion angle: AUC 0.6 For peak ground reaction force: AUC 0.7

Table 3 continued

Study	Outcome measures	Sport	Subject characteristics	Injuries studied	Significant risk factors	Sensitivity and specificity
O'Kane et al. 2015	• Normalised knee separation (prelanding, landing, take-off)	Football	351 F (11 to 14 years)	Acute lower extremity Acute knee	For post-menarchal players: • Normalised knee separation \leq 10th percentile (lower extremity: RR 1.92, 95% CI 1.17-3.15, knee: RR 3.62, 95% CI: 1.18 to 11.09) • 1 SD decrease in normalised knee separation in landing (knee: RR 1.80, 95% CI: 1.01 to 3.23) and in take-off (knee RR 1.66, 95% CI: 1.04 to 2.64)	Sensitivity and specificity not reported
O'Kane et al. 2017	• Normalised knee separation (prelanding, landing, take-off)	Football	351 F (12 to 15 years)	Lower extremity overuse Knee overuse	Normalised knee separation at landing < 10th percentile (lower extremity: RR 2.24, 95% CI: 1.20 to 4.19, knee: RR 3.2, 95% CI 1.52 to 6.71)	Sensitivity and specificity not reported
Padua et al. 2015	• LESS score	Football	348 M, 481 F (13.9 \pm 1.8 years)	ACL	The 1-season risk difference between LESS score \geq 5 and LESS score < 5 was 1.24% (95% CI: 0.12 to 2.36, P=0.01)	ROC curve analysis performed to determine cut-off values. For LESS score 5.17: sensitivity 86%, specificity 71%, AUC 0.78

F=female, M=male, ACL=anterior cruciate ligament, AUC=area under the curve, HR=hazard ratio, RR=risk ratio, CI=confidence interval, IC=initial contact, LESS=Landing Error Scoring System, ROC=receiver operating characteristics

Table 4. Characteristics of studies reporting significant associations between functional movement screen (FMS™) scores and injury risk

Study	Outcome measures	Sport	Subject characteristics	Injuries studied	Significant risk factors	Sensitivity and specificity
Chalmers et al. 2017	<ul style="list-style-type: none"> • The FMS™ composite score • Presence of an asymmetry • Presence of painful sub-test 	Australian football	237 athletes (16.6±0.8 years)	Trauma or medical condition (not illness) causing player to miss match	Presence of side-to-side asymmetry (adjusted to previous injury) <ul style="list-style-type: none"> • ≥1 sub-tests (HR 2.2, 95% CI: 1.0 to 4.8, P=0.048) • ≥2 sub-tests (HR 3.7, 95% CI: 1.6 to 8.6, P=0.003) 	For asymmetry in ≥1 sub-tests: sensitivity 78.4%, specificity 41.0%, negative likelihood ratio 0.53, positive likelihood ratio 1.33 <ul style="list-style-type: none"> • ≥2 sub-tests: sensitivity 66.7%, specificity 71.9%, negative likelihood ratio 0.46, positive likelihood ratio 2.38
Garrison et al. 2015	<ul style="list-style-type: none"> • The FMS™ composite score 	Several collegiate sports	160 subjects (17 to 22 years)	Musculoskeletal injury	FMS™ composite score ≤14 combined with self-reported past injury was associated with a higher risk of injury (OR 15.11, 95% CI: 6.60 to 34.61)	For an FMS™ composite score of ≤14 combined with self-reported past injury: sensitivity of 65%, specificity of 89%, positive likelihood ratio 5.88, negative likelihood ratio 0.39
Mokha et al. 2016	<ul style="list-style-type: none"> • Scores for individual FMS™ component tests • Presence of asymmetry in a bilateral test • The FMS™ composite score 	Football, volleyball, rowing (collegiate)	20 M, 64 F M 20.4±1.3 years F 19.1±1.2 years	Musculoskeletal injury	Side-to-side asymmetry or individual score of 1 were associated with a higher risk of injury (RR 2.73, 95% CI 1.36 to 5.4, P=0.001)	Sensitivity 81.5%, specificity 54.3%
Warren et al. 2015	<ul style="list-style-type: none"> • The FMS™ composite score • Scores for individual FMS™ component tests • Presence of asymmetry in a bilateral test 	Several collegiate sports	89 M, 78 F 18 to 24 y (injured 20.6±1.6years; uninjured 20.0±1.4 years)	Non-contact or overuse injury requiring intervention from athletic trainer	Score of 2 in the inline lunge was associated with a lower risk of injury compared to score of 3 (OR 0.21, 95% CI: 0.08 to 0.59, P<0.05)	Sensitivity and specificity not reported

F=female, M=male, OR=odds ratio, RR=risk ratio, CI= confidence interval

Table 5. Characteristics of studies reporting significant associations between strength measures and the risk of injuries

Study	Outcome measures	Sport	Subject characteristics	Injuries studied	Significant risk factors	Sensitivity and specificity
De Ridder et al. 2016	<ul style="list-style-type: none"> • Isometric hip flexion, extension, abduction, adduction, external rotation and internal rotation strength (Absolute (N) and normalised to body size (N/(body weight x body height²)) 	Football	133 M (10 to 16 years)	Lateral ankle sprains	Increase in hip muscle extension force was associated with a significant decrease in the hazard of ankle sprain injury (HR 0.3, 95% CI: 0.1 to 0.9, P=0.028).	Sensitivity and specificity not reported
Leetun et al. 2004	<ul style="list-style-type: none"> • Isometric hip abduction and hip external rotation strength relative to bodyweight (%) • Side bridge (s) • Back extension (s) 	Basketball, track (collegiate)	60 M, 80 F (M 19.0±0.90 years, F 19.1±1.37 years)	Lower extremity Back	Hip external rotation strength (OR 0.86, 95% CI: 0.77 to 0.97, P=0.013)	Sensitivity and specificity not reported
O'Kane et al. 2017	<ul style="list-style-type: none"> • Isometric hip flexion, extension, abduction, adduction and external rotation strength (Nm) • Concentric hamstring and quadriceps strength (Nm) at an angular speed of 180 °/s. 	Football	351 F (12 to 15 years)	Lower extremity overuse Knee overuse	<p>For knee overuse injury, 1 SD increase in the following strength measures was associated with a decreased risk:</p> <ul style="list-style-type: none"> • Hamstring strength (RR 0.65, 95% CI: 0.46 to 0.91) • Quadriceps strength (RR 0.70, 95% CI: 0.50 to 0.98) • Hip flexor strength (RR 0.72, 95% CI: 0.51 to 1.00) • Hip external rotation strength (RR 0.65, 95% CI: 0.46 to 0.91) 	Sensitivity and specificity not reported

F=female, M=male, RM=repetition maximum, OR=odds ratio, CI= confidence interval, RR=risk ratio, AUC=area under the curve, SD=standard deviation

2.5 The single-leg squat test

The single-leg squat (SLS) test is commonly used in clinical practice to assess knee control. Several different SLS protocols have been utilised, with differences in knee flexion and hand and non-weight-bearing leg placement. In addition to using subjective assessment of frontal plane knee control during the test, SLS performance has been analysed utilising 2D and 3D analysis methods.

2.5.1 Validity and reliability of the two-dimensional analysis

The 2D analysis of frontal plane knee motion has been validated against the 3D motion capture method utilising the side step, side jump, and shuttle run tasks (McLean et al., 2005). The authors concluded that the 2D method provides valid descriptions of frontal plane knee motion for movements in which the joint centres are easily identified. The within-day reliability of the 2D analysis of the frontal plane knee projection angle (FPKPA) during the SLS is reportedly fair to good, while the between-sessions reliability is good to excellent (Munro, Herrington, & Carolan, 2012; Stensrud, Myklebust, Kristianslund, Bahr, & Krosshaug, 2010). According to Stensrud and colleagues (2010), the difference between the first and second 2D video analysis was $3.3^{\circ} \pm 2.9^{\circ}$. The 2D FPKPA can provide a reliable and valid measurement of frontal plane knee motions when the 3D analysis is not available.

2.5.2 Frontal plane knee control during the single-leg squat

Greater FPKPA has been directly associated with greater hip adduction, contralateral posterior pelvic rotation, femoral internal rotation, knee external rotation, and tibial abduction and inversely associated with contralateral pelvic drop during the SLS (Willson & Davis, 2008). As previously mentioned in chapter 2.3.2, hip muscle strength plays a significant role on frontal plane knee control. Improvement in hip abduction strength has been associated with a smaller FPKPA: for every 1% improvement in hip abductor strength normalised to body weight, the FPKPA would improve by 0.2° (Crossley et al., 2011). Individuals displaying medial knee displacement during the SLS have been reported to have

significantly lower gluteus medius to hip adductor and gluteus maximus to hip adductor ratios (Mauntel et al., 2013). This indicates greater hip adductor activation during the SLS, demonstrating that individuals with poor frontal plane knee control use a hip adductor dominant movement strategy. However, there are results demonstrating that hip abductor strength alone might not be a good predictor of FPKPA. Instead, the interaction between decreased hip abductor isometric torque and increased range of passive hip internal rotation contributes to a greater FPKPA (Bittencourt, Ocarino, Mendonça, Hewett, & Fonseca, 2012). The results suggest that individuals with adequate hip stiffness may exhibit better frontal plane knee control. In addition, reduced knee flexion and extension (Claiborne et al., 2006), trunk side flexion (Stickler et al., 2015), and hip external rotation (Willson et al., 2006) strength have been associated with poor frontal plane knee control during the SLS.

The associations between medial knee displacement and hip rotations have been explored in previous studies. Subjects displaying medial knee displacement during the SLS have demonstrated 6° to 7° more peak knee valgus during the SLS compared to subjects without medial knee displacement (Ageberg et al., 2010; Mauntel, Frank, Begalle, Blackburn, & Padua, 2014). Subjects with a knee-medial-to-foot position in the SLS displayed more hip internal rotation in the 3D data compared to subjects with knee-over-foot position (Ageberg et al., 2010). This is contradicted by the findings of Willson and Davis (2008), who detected an unexpected inverse association between FPKPA and hip internal rotation: as FPKPA increased, the hip internal rotation decreased. In addition, one study did not find any association between medial knee displacement during the SLS and hip rotations (Mauntel et al., 2014). The inverse association between FPKPA and hip internal rotation could be explained by contralateral posterior pelvic rotation, that led to a resultant hip external rotation. The authors hypothesised that if the pelvis and trunk were constrained during the SLS, there would be a more significant association between FPKPA and hip internal rotation (Willson & Davis, 2008). The results of the previous studies suggest that no single joint or segment rotation is predominantly responsible for knee valgus during the SLS and that several combinations of hip and knee rotations may result in knee valgus.

2.5.3 Visual assessment

The SLS is a slower movement than, for example the VDJ, and is therefore easier to assess visually (Maclachlan, White, & Reid, 2015). Several studies have investigated the inter- and intra-rater reliability of the visual assessment of the SLS performance. Previous studies have reported the inter-rater reliability of the SLS to be moderate to excellent (Ageberg et al., 2010; Crossley et al., 2011; Harris-Hayes et al., 2014; Junge, Balsnes, Runge, Juul-Kristensen, & Wedderkopp, 2012; Weeks, Carty, & Horan, 2012; Whatman, Hume, & Hing, 2013). However, some studies have found that the inter-rater reliability does not attain the value considered adequate for clinical use (Chmielewski et al., 2007; Poulsen & James, 2011). The intra-rater agreement of the visual assessment has been reported to be substantial to excellent in some previous studies (Crossley et al., 2011; Weeks et al., 2012; Whatman et al., 2013). Poulsen and James (2011) demonstrated a large range in intra-rater reliability (0.38 to 0.94), with two out of the six novice raters not reaching the reliability necessary for clinical use. When comparing the overall and specific rating method, neither rating method produced high intra-rater agreement (Chmielewski et al., 2007).

The experience level of the observers affects inter- and intra-rater reliability. Three previous studies reported that the inter-rater reliability was higher for the more experienced physiotherapists (Crossley et al., 2011; Whatman, Hing, & Hume, 2012; Whatman et al., 2013). Weeks and colleagues (2012) concluded that both the experienced physiotherapists and the students were capable of reliably assessing SLS movement quality, but the clinical experience enhanced inter-rater and intra-rater reliability.

The scale used of the rating affects the reliability. Previous reliability studies have used dichotomous (Ageberg et al., 2010; Whatman et al., 2013), three-point (Chmielewski et al., 2007; Crossley et al., 2011; Stensrud et al., 2010), four-point (DiMattia et al., 2005; Junge et al., 2012) and ten-point ordinal scales (Weeks et al., 2012). In addition, a rating method in which three segments (trunk, pelvis and thigh/hip) were rated separately and the sum of segment scores was used for reliability, has been used (Chmielewski et al., 2007; Poulsen & James, 2011). The use of dichotomous rating improves both the inter- and intra-rater agreement (Whatman et al., 2012).

Previous studies have considered the contributions of different body segments to the visual assessment. Peak knee flexion explained 33% of the variance in the physiotherapist ratings of the SLS performance (Weeks et al., 2012). The prediction

was strengthened by 21% when peak hip adduction was added and by 10% with the addition of knee medio-lateral displacement. The physiotherapy students did not seem to consider hip movement in their rating as did the experienced physiotherapists. Junge and colleagues (2012) reported that the inter-rater agreement was best for trunk displacement and that the body component most difficult to judge was the knee.

The correlation between the 2D video analysis and the visual assessment of SLS has been studied previously (Harris-Hayes et al., 2014; Stensrud et al., 2010). Harris-Hayes and colleagues (2014) classified the lower extremity motions during the SLS as dynamic valgus, no change, or dynamic varus. In the study by Stensrud and colleagues (2010), the SLS performance was rated to be “good”, “reduced”, or “poor”. The agreement between the 2D analysis and the visual assessment of the SLS performance was reported as good to excellent (Stensrud et al., 2010) and substantial (Harris-Hayes et al., 2014). DiMattia and colleagues (2005) evaluated the validity of visual assessment as compared to the 2D analysis. Two raters observed the SLS performances on a four-point graded scale. The two raters agreed as to knee valgus 66.6% of the time and hip adduction 71.3% of the time. For knee valgus, the specificity was moderate to high and the sensitivity was low to moderate. For hip adduction, the specificity was high and the sensitivity was low.

Using a dichotomous rating of visual assessment by grading the subjects as “good” and “poor” performers has been used in several studies to explore the differences between the performances. Typically, the poor performers demonstrate a greater hip adduction angle (Hollman, Galardi, Lin, Voth, & Whitmarsh, 2014; Horan, Watson, Carty, Sartori, & Weeks, 2014) and less hip abduction torque (Crossley et al., 2011). Poor performance has also been associated with a greater hip flexion angle (Hollman et al., 2014), smaller knee flexion angle (non-standardised squat depth) (Horan et al., 2014), reduced trunk side flexion force (Crossley et al., 2011) and greater medio-lateral knee displacement (Horan et al., 2014). The good performers had an earlier onset timing of both the anterior gluteus medius and the posterior gluteus medius compared to the poor performers (Crossley et al., 2011). Frontal and transverse plane hip motion and gluteus maximus recruitment contribute significantly to the variance in frontal plane knee kinematics (Hollman et al., 2014).

2.5.4 Range of motion

ROM in the joints of the lower extremity could contribute to frontal plane knee movements during the SLS. Mauntel and colleagues (2013) set out to study whether subjects displaying medial knee displacement have different passive ROM than those without medial knee displacement. Joint angles for passive ROM were measured for the hip external rotators, hip internal rotators, hamstrings, iliotibial band, iliopsoas, and femoral anteversion. The valgus group displayed less dorsiflexion passive ROM and greater posterior movement of the talus. Limited dorsiflexion could contribute to excessive rear foot pronation and result in increased frontal plane knee motion. In another study, the hip internal rotation ROM alone was not a significant factor, but the interaction between hip abductor isometric torque and passive hip internal rotation ROM was associated with the FPKPA (Bittencourt et al., 2012).

2.5.5 Single-leg squat performance in adolescents

Most studies on the SLS have been performed on adult populations. Agresta and colleagues (2016) investigated the influence of maturation on the SLS performance in physically active children and adolescents aged 8 to 17 years (mean age 13.3 years). Maturity level was defined using the peak height velocity (PHV) maturity offset (Mirwald et al., 2002). Although maturity status or sex did not influence the visually assessed SLS scores, chronological age was associated with the SLS performance: the SLS score improved by 0.4 points for every one-year increase in age. The authors hypothesised that the large variation in the SLS performance might explain why there is no association between maturity status and the SLS performance. Ugalde and colleagues (2015) studied the SLS performance of adolescent athletes with a mean age of 13.8 ± 1.8 years. The SLS performance was visually assessed by a single observer and rated to be “positive” (signs of abnormal response) or “negative”. Among the 142 subjects, 51% displayed signs of abnormal responses (arms flailing, the Trendelenburg sign, and/or knee valgus collapse) during the SLS. Comparing the groups rated positive or negative, there were no differences in age, sex or BMI.

2.5.6 Differences related to sex

As previously presented in chapter 2.3.2, poor frontal plane knee control is more prevalent in females. Previous studies have reported several sex-related differences in the SLS performance, but the findings are partly contradictory. It has been reported that in the SLS, females demonstrate significantly more ankle dorsiflexion, ankle pronation (Zeller et al., 2003), hip adduction (Baldon et al., 2011; Graci, Van Dillen, & Salsich, 2012; Nakagawa, Moriya, Maciel, & Serrão, 2012; Zeller et al., 2003), hip flexion and external rotation (Zeller et al., 2003), ipsilateral trunk lean (Nakagawa et al., 2012), knee abduction (Baldon et al., 2011; Graci et al., 2012; Nakagawa et al., 2012), contralateral pelvic drop (Baldon et al., 2011), and less trunk lateral flexion (Zeller et al., 2003) compared to males. In addition, females demonstrate less hip flexion during the SLS than males (Dwyer et al., 2010). Females have also been reported to exhibit greater peak pelvis rotation, peak hip internal rotation, hip adduction range, hip rotation range, and, at the knee, greater medio-lateral distance compared to males (Weeks, Carty, & Horan, 2015). Graci and colleagues (2012) noticed that females rotated the pelvis toward the weight-bearing leg while males rotated toward the non-weight-bearing leg during the SLS. In adolescents, previous studies have reported that no sex-related differences in the SLS were identified (Agresta et al., 2016; Ugalde, Brockman, Bailowitz, & Pollard, 2015).

During the SLS, females have been found to activate their gluteus medius and gluteus maximus muscles at a greater percent of their maximum effort compared to males (Dwyer et al., 2010; Nakagawa et al., 2012). In addition, greater rectus femoris activation levels in females compared to males have been reported (Dwyer et al., 2010; Zeller et al., 2003). Taken together with the greater hip adduction range, it appears that females were attempting to use the rectus femoris to control their knee during the SLS.

2.5.7 Patients with patella-femoral pain syndrome

Poor frontal plane knee control is considered to be a risk factor for patella-femoral pain syndrome (PFPS). Previous studies have identified reduced frontal plane knee control in patients with PFPS compared with healthy controls (Herrington, 2014; Levinger, Gilleard, & Coleman, 2007; Scholtes & Salsich, 2017; Willson & Davis, 2008). Subjects with PFPS have been shown to demonstrate significantly greater ipsilateral trunk lean, contralateral pelvic drop, hip adduction and knee abduction

during the SLS compared to the healthy controls (Nakagawa et al., 2012). There was 18% less hip abduction and 17% less hip external rotation strength in the PFPS group than in the healthy controls. The effect of movement instruction on trunk and lower extremity kinematics during the SLS in females with dynamic knee valgus and patella-femoral pain has also been studied (Graci & Salsich, 2015). In the corrected condition, subjects demonstrated increased lateral flexion of pelvis toward the weight-bearing leg and decreased femoral adduction and internal rotation. Lower pain levels were associated with decreased femoral adduction.

2.5.8 Patients with an ACL injury

Return to unrestricted activity after an ACL reconstructive surgery is often based on time instead of being based on the function of the operated leg. The SLS can be used to identify neuromuscular deficits in the operated leg which can be used to assess the progress of the rehabilitation process and readiness for unrestricted activity. SLS to 60° knee flexion has been used for neuromuscular evaluation six months after an ACL reconstruction on adults (Hall, Paik, Ware, Mohr, & Limpisvasti, 2015). A single observer graded the performance using the video footage. The performance was rated to be “poor” or “good”. Out of the 33 patients, 15 (45%) demonstrated poor performance on the operated leg. The poor performers were significantly older than the good performers. Patients with poor performance had significantly lower hip abduction strength in the operated leg compared to the non-operative leg. Authors concluded that the visual assessment of SLS performance can be used to identify neuromuscular deficits after ACL reconstruction and may be used to assess whether the patient is ready for unrestricted activity.

The differences in the SLS performance between ACL-injured patients and healthy controls before an ACL reconstruction have also been investigated (Yamazaki, Muneta, Ju, & Sekiya, 2010). Males demonstrated significantly less knee and hip external rotation, less knee flexion, and more varus on the injured leg compared to the uninjured leg. Females demonstrated more knee varus on the injured leg compared to the uninjured leg. Comparing ACL-injured females and males, females demonstrated more external hip rotation and knee valgus on both the injured and uninjured legs than males. Comparing the uninjured leg of the ACL-injured to the dominant leg of the controls, ACL-injured males demonstrated significantly less external knee rotation and ACL-injured females demonstrated

significantly more external hip rotation and knee flexion and less hip flexion compared to the controls.

2.5.9 Correlation with other screening tests

Previous studies have compared the SLS performance to other screening tests to investigate if the tests identify the same individuals as “high-risk” subjects. In a previous study, the performance between the SLS, vertical drop jump (VDJ), and single-leg vertical drop jump (SLVDJ) were compared using both the visual assessment and 2D analysis (Stensrud et al., 2010). The agreement of the visual assessment between the three tests was poor, while the agreement of the 2D analysis was low to moderate. The authors suggested that the SLVDJ is an inadequate tool to evaluate knee control, since less than 10% of the subjects were assessed as having poor knee control in this test while the proportion was much higher in the other two tests. Since the SLS and VDJ identify different subjects, both tests should be used to screen for poor knee control. Approximately 20% of the subjects displaying poor knee control would not have been identified using only one test. The SLS to 30° knee flexion and VDJ were used in a study on middle school and high school athletes (Ugalde et al., 2015). One observer rated the SLS performance as positive (displaying signs of poor lower extremity biomechanics, reduced core strength, or hip abductor weakness) or negative. Among the athletes with positive SLS score, 51% displayed more dynamic valgus in the VDJ compared to the athletes with negative scores.

2.5.10 Differences in the SLS test protocols and interpretation

The specific SLS test procedure that is used greatly impacts the findings. In previous studies, the squat depth used in the test protocol, measured by knee flexion angle, has varied between 30° (Ugalde et al., 2015) and 90° (Stensrud et al., 2010). Studies have also used non-standardised squat depth (Horan et al., 2014; Weeks et al., 2012) or have instructed the participants to squat down as far as possible while maintaining balance (Boudreau et al., 2009; Crossley et al., 2011; Zeller et al., 2003). Most studies have utilised knee flexion angle of 60° (Agresta et al., 2016; Bittencourt et al., 2012; Chmielewski et al., 2007; Claiborne et al., 2006; DiMattia et al., 2005; Hall et al., 2015; Harris-Hayes et al., 2014; Mauntel et al., 2013, 2014; Stickler et al., 2015). Horan and colleagues (2014) did not standardise

the knee flexion to resemble clinical conditions. However, the authors concluded that future studies should apply a standardised knee flexion angle.

In addition to squat depth, there are also other differences in the test protocols, such as the positioning of the non-stance leg and arms. Comparing three different positions of the non-stance leg: in the front of, next to and behind the weight-bearing leg, Khuu and colleagues (2016) noticed that leg position affects the mechanics of the trunk, pelvis, and lower extremity. When comparing studies on SLS it must be considered that different SLS protocols may yield different results even in the same cohort.

2.6 Limitations in previous prospective injury risk factor studies

There are several methodological aspects in the previous sports injury risk factor studies, which might influence the level of evidence of these studies. The variability in injury definitions and injury and exposure data registration methods not only make comparisons between injury risk factor studies difficult, but also contribute to the value of these studies.

Capturing all sports injuries is complex. It has been previously reported that there are discrepancies in the number of injuries (Nilstad, Bahr, & Andersen, 2014) and time loss (Emery et al., 2005) between different registration methods. Utilising weekly text messaging has been shown to capture more injuries than team medical staff reports, but not all. Møller et al. (2018) reported some false-negative answers in their study among adolescent handball players utilising text messaging. This was hypothesised to be related to the burden related to the phone interview which followed when the athlete reported an injury. Schiff and colleagues (2010) reported that injury rates reported using Internet-based surveys completed weekly by parents were very similar to those reported by athletic trainers. However, there was discrepancy between the two methods and both methods missed some injuries due to the different interpretations of injury definition.

Several different injury registration methods have been utilised in the previous studies. In high school and collegiate sports, athletic trainers (Butler, Lehr, Fink, Kiesel, & Plisky, 2013; Gribble et al., 2015; Hewett et al., 2005) and coaches (Plisky et al. 2006) have collected the injury data. Weekly visits from the research staff (Padua et al., 2015) and data recorded by team designates (a volunteer coach or parent) (Emery et al., 2005) have been utilised in football clubs. The validated

Internet-based survey e-mailed to the parent each week has also been utilised in youth football (O’Kane et al., 2015, 2017).

Injury definition is a potential source of bias and can affect the validity of injury data collection. To capture all musculoskeletal injuries and complaints is more complex than collecting all ACL injuries: ACL injury is a major injury and would not go unreported by the athlete, athletic trainer, parent, or coach. In adolescent athletes, only collecting injuries which require medical attention would exclude a large share of injuries, since youth teams don’t always have medical staff and many injuries are treated at home. Using time-loss as a criterion can reduce the different interpretations of injury definition, which has been reported as a limitation of data collection (Schiff et al., 2010).

In sports injury studies, selection bias is a common methodological issue as participants are not selected randomly; instead teams, athletic departments, school boards, or individual athletes are recruited, and usually from the geographic area of the research facility. It is possible that teams or athletes that consider injury prevention a priority are more willing to participate. This is a concern in many studies, but especially when a convenience sample including only one team or volunteers from one college is recruited. For assessment of internal validity, it is important to report how well the study cohort represents the population. Usually the number of recruited teams/schools/clubs/athletes is reported, in addition to the number that agreed to participate. However, Hewett and colleagues (2005) only reported the number of athletes participating in the study but the number of high schools and the number of eligible female football, basketball, and volleyball players was not reported. External validity can be limited by limitations in internal validity (Emery, 2005). However, the generalisability of the results is also related to the sport, age, level of competition, and type of injury.

In risk factor studies, establishing a healthy cohort at baseline is important in order to avoid the risk of reverse causality (Asker et al., 2018). For example, Gribble and colleagues (2015) had all their participants cleared for full participation by physician. Most studies have excluded athletes with a recent injury or have reported being injury free at baseline as an inclusion criteria (Chalmers et al., 2017; Garrison et al., 2015; Holden et al., 2017; Leetun et al., 2004; Mokha et al., 2016; O’Kane et al., 2015, 2017; Padua et al., 2015; Plisky et al., 2006; C. A. Smith et al., 2015; Warren et al., 2015). However, recording the status of recent injury or injury at baseline is not always reported (Hewett et al., 2005).

Reporting injury incidence as the number of injuries/1000 hours of training and/or match play instead of number of injuries/1000 athlete exposures or

number of athletes is preferred. However, collecting individual exposure data is troublesome. Coaches or team designates reporting the length of the practise and athlete participation is often used, as well as self-reports. Lack of exposure measures has been reported as a limitation in some studies (Garrison et al., 2015; Gribble et al., 2015). Gathering valid exposure data is difficult. Recruiting volunteer team designates, Emery and colleagues (2005) were able to collect weekly exposure sheets from 97% of the team weeks. Comparing exposure measures collected via text messages to the data collected by on-field observers, Møller and colleagues (2018) reported an average difference of 1.1 hour in weekly training exposure and 0.2 hours in weekly match exposure. Since some “response fatigue” was observed in the text message data collection, there is a chance that the validity of this measurement tool is lower for longer data collection periods.

Large cohorts are needed to examine the associations between risk factors and injuries. For small to moderate associations, about 200 injured subjects and for moderate to strong associations, 20–50 injury cases are needed (Bahr & Holme, 2003). This means that the size of the cohort is hundreds of athletes or even over 1,000 if the incidence of the analysed injury type in the population is low. If the cohort is too small, it is possible to commit type II error. It should be taken into consideration that non-significant outcome does not always confirm that no association exist, instead the statistical power could be too low. For example, Leppänen and colleagues (2017) considered that their non-significant findings on knee valgus as a risk factor could be due to limited power. The limited statistical power could also be the case in the work of Bardenett et al. (2015). They reported non-significant findings on the association between the FMS component and total scores and musculoskeletal injury in a cohort of 167 high school athletes from several individual and team sports. However, no power calculation or other argument for how the study size was arrived at was reported. It is recommended that statistical power analysis is performed a priori (Portney & Watkins, 2009). However, when exploring new potential risk factors, there is no previous on the effect size, which is needed for the power calculation. Power calculations are not commonly reported in the previous studies. Smith and colleagues (2015) performed power calculations a priori based on the findings of a previous study on the SEBT (Plisky et al., 2006). In the screening test studies reporting statistically significant findings (Tables 2–5), the number of subjects ranges from 76 (Holden et al., 2017) to 539 (Gribble et al., 2015).

Since large cohorts are essential in order to identify risk factors, usually multiple investigators are needed to complete baseline testing (Chalmers et al., 2017;

Gribble et al., 2015; Leppänen et al., 2017; C. A. Smith et al., 2015). This is a potential source of measurement bias. Education of investigators is usually reported as a method of controlling the reliability of the measurements between testers. Addressing the reliability and validity of the selected screening tests is important for the interpretation of the results. Some studies fail to report whether baseline testing was completed by a single tester or multiple investigators. This information is valuable and should be reported.

One limitation of the studies can be the limited translation of the test results to sporting tasks (De Ridder et al., 2016). For research purposes, the tests need to be standardised and therefore do not reflect the real-life movements, such as double-legged landing from heading in football and single-leg stance phase in direction change in floorball. However, as we need to identify more risk factors and research their interaction, the use of these tests, when reliable and valid, is justified.

Sports injuries are multifactorial and there are several confounding factors. For example, for ACL injuries in female team sport athletes, Hewett and colleagues (2005) acknowledged that school, team, age/grade, aggressiveness, foot pronation, quadriceps angle, femoral notch width, reliable menstrual status reporting, and blood hormone levels could be potential confounders. The known and potential risk factors which may be unevenly distributed among the injured and uninjured athletes should be chosen as confounders before risk factor analysis are performed (Asker et al., 2018). However, this is not always the case in risk factor studies. With the list of potential confounders being as long as the one for ACL injuries, controlling for confounders is difficult.

3 PURPOSE OF THE STUDY

In order to reduce the rates of adolescent sports injuries, we must identify risk factors associated with an elevated risk of injury in different sports and age groups. To estimate the efficiency of injury prevention methods, we must have current knowledge as to the extent of the problem (van Mechelen, Hlobil, & Kemper, 1992). The potential for the SLS to be developed into a screening tool has been previously hypothesised (Mauntel et al., 2014; Ugalde et al., 2015). However, there are no previous studies on the association between the SLS performance and the risk of future injuries. This is somewhat surprising considering the number of previous studies investigating different aspects of the SLS. In light of the clinical application of the SLS test as a knee control test, this knowledge gap is significant and therefore must be addressed by prospective risk factor studies.

This doctoral dissertation focuses on the first two steps in van Mechelen's sequence of injury prevention (van Mechelen et al., 1992). Firstly, in Study I, the extent of the problem of PA-related injuries among Finnish adolescents is determined. Next, reliability (Study II) and risk factors (Studies III and IV) are investigated.

The aims of this thesis were as follows:

- 1) to determine the prevalence of physical activity-related injuries among adolescents in Finland in organised sports, school sports, and leisure time PA (I);
- 2) To examine the correlation between the visual assessment and 2D video analysis of the single-leg squat performance and determine the intra-rater and inter-rater reliability of the visual assessment of knee control (II);
- 3) To investigate the association between the frontal plane knee projection angle measured during the single-leg squat and new acute lower extremity injury among young team sport athletes (III and IV);

- 4) To determine the suitability of the single-leg squat test as a screening tool to predict future injury in adolescent team sport athletes (III and IV);
- 5) To explore the age, sex, and side-to-side differences in frontal plane knee control (III and IV);
- 6) To explore the association between side-to-side difference in frontal plane knee control and the risk of lower extremity injuries in young football players (IV).

4 MATERIALS AND METHODS

This doctoral thesis and the related original publications are based on three separate studies: the Adolescent Health and Lifestyle Survey (Study I), the Predictors of Lower Extremity Injuries in Team Sports study (Studies II and III) and the Sports Injury Prevention in Youth Football study (Study IV). The structure of the thesis is presented in Figure 4.

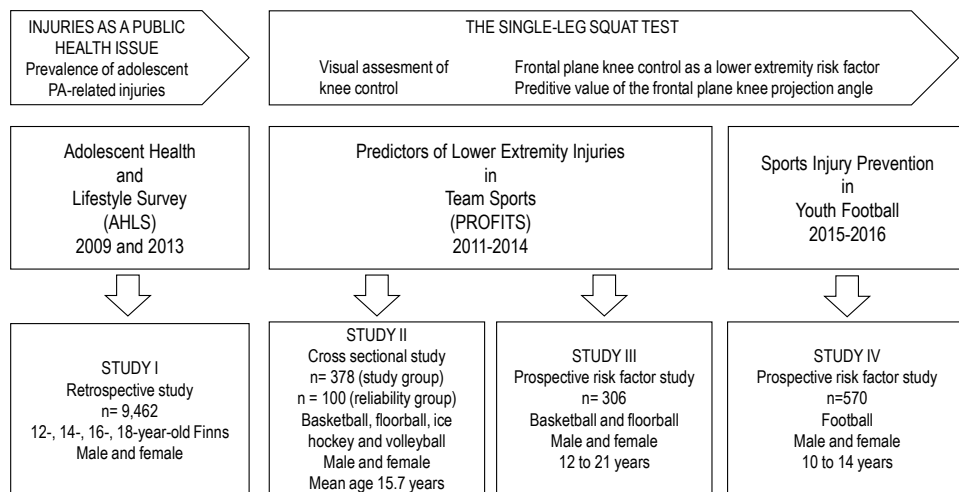


Figure 4. The studies comprising this doctoral dissertation.

4.1 Adolescent physical activity-related injuries (I)

4.1.1 Study design and subjects

The first study is a retrospective survey study. This study is part of the Adolescent Health and Lifestyle Survey (AHLS), a nationwide survey system that monitors the health and health-related lifestyle of 12-, 14-, 16- and 18-year-old Finns. The AHLS

was established in 1977, and the survey is carried out every second year. Questions regarding PA-related injuries in sports club activities, school sports, and leisure time PA were included in the survey in 2009 and 2013. The study protocol was approved by the Ethics Committee of Tampere Region (reference Lausunto 2/2010) and the Ethics Committee of the Pirkanmaa Hospital District (reference ETL code R06226). Written informed consent was not required.

For each study year, a nationally representative sample of 12-, 14-, 16-, and 18-year-old Finns was obtained from the Population Register Centre. The dates of birth used in the sample were different for each study year to secure a sample consisting of different subjects each year.

In 2009, a total of 5,516 out of the sample of 9,920 adolescents responded. In 2013, 4,158 out of 9,398 responded. The response rate for the combined data of 2009 and 2013 was 50%. Due to inconsistencies in the responses, 212 subjects were excluded. A total of 9,462 subjects were included in the analysis, among which 59% were girls and 41% were boys.

4.1.2 Outcomes and data collection

The data was collected by a 12-page structured questionnaire. The questionnaire was mailed in February of the study year. Enclosed with the questionnaire were a personal user name and a password which could be utilised to answer the questionnaire online. Three follow-up enquiries were sent to non-respondents.

Injury prevalence in sports club activities, school sports, and leisure time PA was measured separately. For the sports club activities, prevalence refers to the proportion of subjects reporting at least one injury during the past 12 months among the subjects who reported participating in sports club activities. For school sports, prevalence was defined as the proportion of injured subjects among those who reported being students. For leisure time PA, prevalence was defined as the proportion of subjects injured during leisure time PA among the subjects reporting participation in leisure time PA.

Three separate questions were used to collect injury data in the three settings: *“During the past year, have you suffered an injury while participating in sports club activities/physical education class, or instructed student sports/other leisure time physical activities (not in a sports club)?”* In 2009, the answer options were “No”, “Once”, and “Twice or more”. In 2013, the options were “No”, “Once”, “Twice”, and “Three times or

more”. To combine the 2009 and 2013 data, a dichotomous variable of injury status was created with the categories “Not injured” and “Injured at least once”.

Frequency of participation in sports club activities and leisure time PA was determined. Exercise intensity was determined from the following question: *“When I participate in sports or other physical activity, I usually experience: no sweating or getting out of breath/some sweating or getting out of breath/moderate sweating or getting out of breath/extensive sweating or getting out of breath/ I do not exercise.”* To record the number of students, information as to student status was requested.

4.2 Visual assessment of the single-leg squat performance (II)

4.2.1 Study design and subjects

The second study is a reliability study on a cohort of young male and female basketball, floorball, ice hockey, and volleyball players. This study is part of the Predictors of Lower Extremity Injuries in Team Sports (PROFITS)-study. The study protocol was approved by the Ethics Committee of Pirkanmaa Hospital District (ETL code R10169). Written informed consent was obtained from all subjects when they entered the study. For subjects younger than 18 years, written consent was obtained from the parent/legal guardian. A total of 478 subjects participated in the baseline SLS. Among them, 378 formed the study group (249 females, 129 males) and 100 (32 females, 68 males) were randomly assigned to the inter-rater reliability group. The number of subjects in each stage is presented in Figure 5.

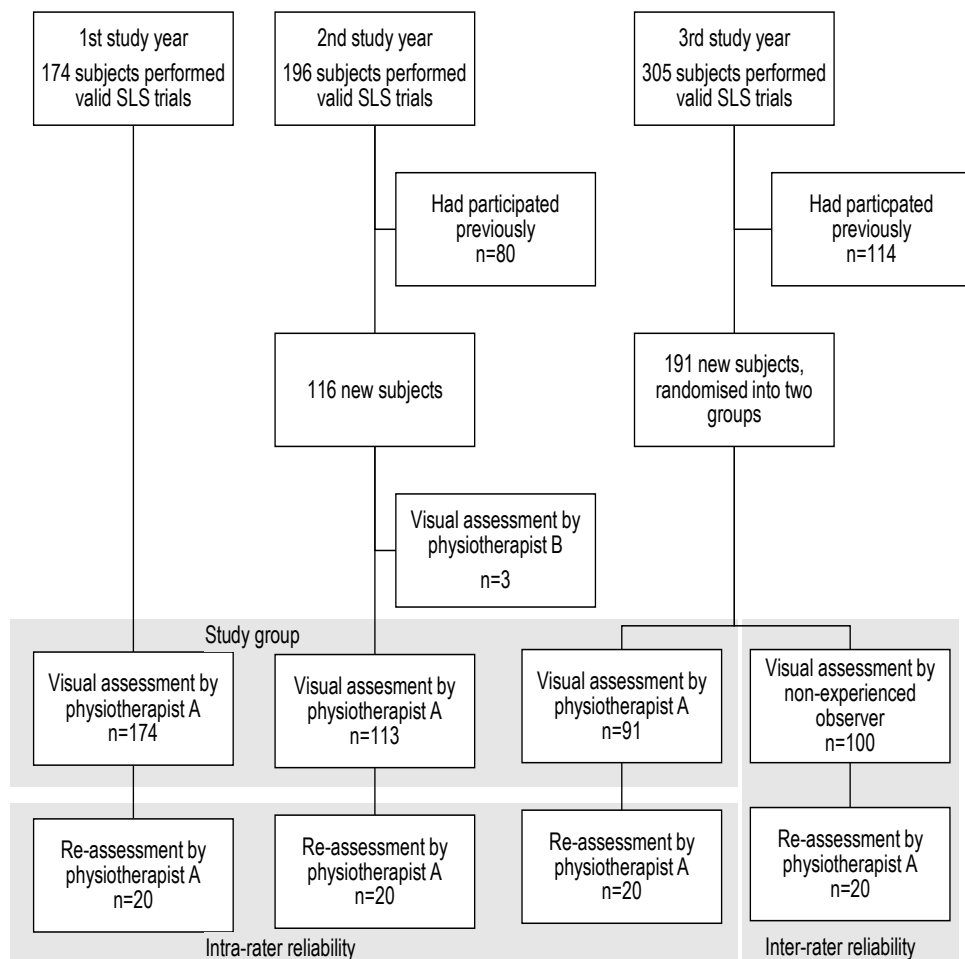


Figure 5. Number of subjects in each stage of Study II

4.2.2 Outcomes and data collection

The subjects participated in the baseline SLS during pre-season in 2011, 2012 or 2013. The SLS test procedure was based on the work of Stensrud and colleagues (2010). The subjects wore indoor sporting shoes and shorts and females wore a sports top. Square pieces of sports tape were placed on the right and left anterior superior iliac spine (ASIS) and the right and left tuberositas tibiae. Next, a warm-up consisting of 2 x 8 repetitions of 2-legged squats and 2 x 5 repetitions of 2-legged

jumps was performed. As a modification of the original procedure, calf stretches were not included in the warm-up. To standardise the knee flexion angle to 90° , the subjects performed a 2-legged squat and knee flexion was measured using a plastic goniometer (Baseline). When the subject reached the 90° knee flexion, a string with a small metal object in the end was attached to the lateral side of the thigh. The length of the string was adjusted so that the metal object would slightly touch the metal plate on which the subject was standing. This was performed on the right and left leg. To perform the SLS, the subject would stand on a metal plate on one leg, holding their hands on the waist and focusing eyes straight forward and squat until they heard the metal object touch the metal plate (Figure 6). Each subject practiced the SLS once before attempting to perform three valid trials on each leg, starting on the right leg. A trial was deemed invalid if the non-weight-bearing leg was held in the front or on the side or if it touched the ground, if the subject looked down, lost balance or removed hands from the waist.

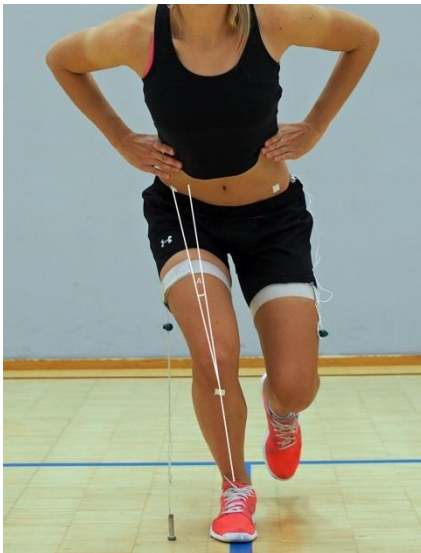


Figure 6. An athlete demonstrating the single-leg squat test. The metal object on the lateral side of the weight-bearing leg touches the ground when 90° knee flexion is achieved. The frontal plane knee projection angle measured in the 2D analysis is displayed. From Räsänen et al. 2018, reproduced in accordance with the Creative Commons Attribution licence.

For the study group, the SLS performance on each leg was visually assessed by a single physiotherapist and recorded using a high definition digital video camera (HXR-NX70E, Sony, Japan). The camera was placed 4.5 meters from the front edge of the metal plate, and the physiotherapist was seated behind the camera. The

performance was graded on a 3-point scale as “good”, “reduced”, or “poor”. Good performance was described as no significant lateral tilt of the pelvis, no obvious valgus motion of the knee, and no medial/lateral movement or shivering during a trial. Reduced performance was described as some lateral tilt of the pelvis, and/or slight valgus movement of the knee, and/or some medial/lateral movement or shivering during a trial. Poor performance was described as lateral tilt of the pelvis, and/or knee moving clearly into a valgus position, and/or clear medial/lateral movements of the knee. The performance was rated based on the poorest performance. Each leg was rated separately.

To establish the intra-rater reliability of the visual assessment, a random sample of 20 subjects per each of the three test years was drawn. The SLS performances of these 60 subjects were re-assessed by the physiotherapist six months after the conclusion of the last test period. The physiotherapist viewed each video recording once on a 22-inch screen without stopping it and rated the performance using the same scale as that used in the initial assessment.

For the inter-rater reliability, the subjects entering the study during the third year were randomised into two groups: the inter-rater reliability group and the study group. The SLS performances of the inter-rater reliability group were assessed by a non-experienced observer and the physiotherapist assessed the performances of the study group. Before the assessments, the physiotherapist trained the non-experienced observer. Firstly, they studied the written instructions. Secondly, they viewed video recordings of 10 subjects performing the SLS and assessed the performances, then compared the results and discussed discrepancies. Thirdly, the non-experienced observer and the physiotherapist simultaneously assessed the SLS performances of 15 subjects. Again, the results were compared and discussed. Among the 100 subjects in the inter-rater reliability group, a random sample of 20 subjects was drawn. The physiotherapist viewed these performances from the video recordings and graded them.

In the 2D video analysis, Java-based computer software (ImageJ, National Institutes of Health) was used to estimate the FPKPA. The FPKPA was calculated as the intersection of a line created by the ASIS and knee joint centre and the line created by the knee joint centre and the ankle joint centre (Figure 6). Neutral alignment was considered 0°, positive values represented valgus alignment and negative values represented varus alignment. The FPKPA was calculated at the point of the greatest knee flexion angle, which was assessed as the lowest point of the pelvis height during the SLS. The 2D video analysis was performed by the primary investigator (A.R.).

At baseline, the height and weight of each subject were measured and subjects filled out a questionnaire. The information regarding dominant leg was derived from the questionnaire. Dominant leg was defined as the preferred leg to kick a ball or take off.

4.3 Knee control and injury risk in young floorball and basketball players (III)

4.3.1 Study design and subjects

The third study is a prospective cohort study that is part of the PROFITS study, similarly to Study II. The previously described cohort was narrowed down to floorball and basketball players, aged 21 years and under when they entered the study. The subjects participated in a baseline SLS and a 12-month injury registration. A total of 367 subjects, who were free from injury, participated in the baseline SLS. Six subjects were excluded from the study for not performing a sufficient number of valid trials, and 55 subjects dropped out during the follow-up. The number of subjects in each stage of the study is presented in Figure 7.

4.3.2 Outcomes and data collection

The baseline measurements and the 2D video analysis have been described in detail in chapter 4.2.2. For previous injury status, the acute time-loss injuries the athletes had sustained during the past 12 months were derived from their baseline questionnaire, as well as the information regarding the dominant leg.

Injury definition was based on the work of Fuller and colleagues (2006), and injury was defined as an acute lower extremity (hip, groin, thigh, knee, lower leg, ankle, foot) injury that resulted in the player being unable to fully participate in training or match play for at least 24 hours. The injuries were recorded by the team coach or another designated member of the coaching staff or team. To register the injuries, study physicians and study assistants contacted the teams weekly. When an injury was reported, the study physician contacted each injured player and collected details in a standardised phone interview regarding the time, place, cause, type, location, and the time-loss due to injury. Team coaches recorded athlete

participation in team practice and games and e-mailed the participation records to the study group each month for exposure registration.

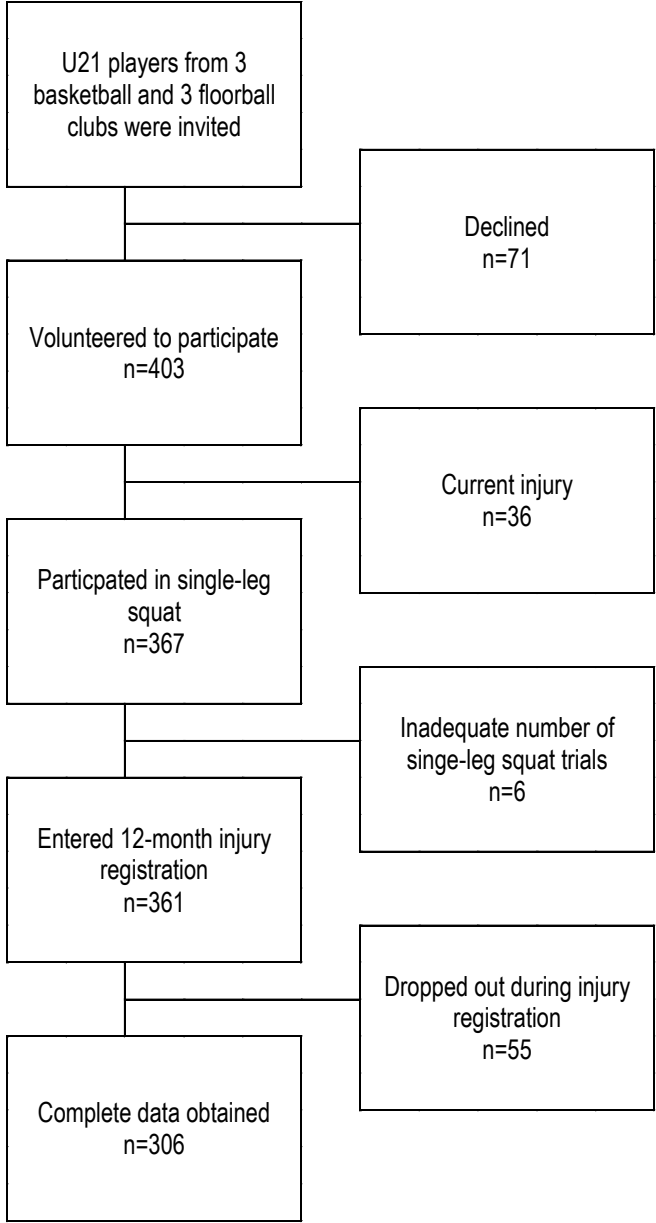


Figure 7. Number of participants in each stage of Study III

4.4 Knee control and injury risk in youth football players (IV)

4.4.1 Study design and subjects

This study is a cohort study on the control group of a cluster-randomised controlled trial, the Sports Injury Prevention in Youth Football (ISRCTN14046021). The participants were football players aged 10 to 14 years. They were official members of teams participating in the Sami Hyypiä Academy, a player development monitoring program of the Eerikkilä Sports Institute. The control group consisted of 737 subjects. Subjects had to be free of a major injury at baseline to be eligible. Subjects who did not participate in the baseline SLS ($n=163$) or injury surveillance ($n=6$) were excluded. In addition, subjects who dropped out during the injury surveillance ($n=10$) were excluded. A total of 558 subjects were included in the analysis. Among them, 445 were boys and 113 were girls. Written informed consent was acquired from the participating player and their parent/legal guardian. The study was approved by the Ethics Committee of Pirkanmaa Hospital District (ETL-code R13110). The players were categorised into age groups of less than 11 years (U11), less than 12 years (U12), less than 13 years (U13), and less than 14 years (U14) according to their age at the time of the baseline test. The 18 players who had not yet turned 10 years old were included in U11.

4.4.2 Outcomes and data collection

The SLS test procedure and the 2D video analysis have been described in chapter 4.2.2. A small alteration to the test procedure was made in that the warm-up was excluded. In this study, the high-definition video camera (Panasonic HDC-SD9C, Panasonic, Japan) used to capture knee joint kinematics was different from that in Studies II and III. In addition to the FPKPA, side-to-side difference in the mean FPKPA between the two lower extremities, and the ability to perform valid SLS (yes/no) were explored as potential risk factors.

The players participated in the baseline SLS and height and weight measurements during their team's player development monitoring event at the Eerikkilä Sports Institute. Using height and weight, BMI (kg/m^2) was calculated. Each player completed a questionnaire with information regarding date of birth, sex, years of playing football, dominant leg, family history of musculoskeletal

disorders, chronic illnesses, orthopaedic surgeries, menstrual cycle, and previous injuries.

An injury was defined based on the consensus statement by Fuller and colleagues (2006) as *“any physical complaint sustained by a player that result from football training or playing, causing a need for medical attention or time loss from fully football activities.”* This study was limited to acute lower extremity (hip/groin/thigh/knee/shin/calf/ankle/foot) injuries, which were categorised as contact or non-contact according to the injury situation. Non-contact injury was defined as an injury that occurred without direct contact to the injured body part. During the 20-week injury registration, from January to June, a text message was sent at the end of the week to each player’s parent/legal guardian with the question *“Has your child had any musculoskeletal complaints or injuries during the previous seven days?”* Options provided for reply were “Yes” and “No”. When an injury or a musculoskeletal complaint was reported, the research assistants contacted the injured player’s parent/legal guardian to collect details of the injury using a standardised phone interview. The player was defined as injured until he/she was able to return to normal training and match play.

4.5 Statistical methods

In Study I, McNemar’s test for two related samples was used to analyse the differences in injury prevalence between sports club activities, school sports, and leisure time PA. To analyse the differences in injury prevalence between age groups, Pearson’s chi-square test was used. Odds ratios obtained from multivariate logistic regression analysis were used to analyse the association between the prevalence of sports club injuries and sports club participation frequency, between leisure time injury prevalence and leisure time PA frequency, and between the prevalence of PA-related injuries and exercise intensity. Age and sex were entered into each multivariate model to adjust for their potential confounding effect.

In Study II, one-way analysis of variance was used to test the differences in the mean FPKPA between the subjectively assessed groups (good/reduced/poor performance). To determine intra- and inter-rater reliability of the subjective assessment, Cohen’s kappa test was utilised. To determine the correlation between the subjective knee control assessment scale (good/reduced/poor performance) and the FPKPA, Spearman’s rank correlation coefficient was used. The kappa values and the correlation coefficient were interpreted as very good (0.81 to 1.00),

good (0.61 to 0.80), moderate (0.41 to 0.60), fair (0.21 to 0.40), and poor (<0.20) (Altman, 1991).

In Study III, to compare the injured and uninjured players, the Mann-Whitney U test was used to test the variables that were not normally distributed (age, BMI, exposure variables) and independent samples *t* test was used for normally distributed variables (height, weight, FPKPA). The chi-square test was used for categorical variables (sex, sport). To consider the possible non-linear relationship between intrinsic factors and the risk of injury, categorical variables were formed based on the continuous variables utilising the cohort mean and standard deviation (SD) (Bahr & Holme, 2003). Age, height, weight, BMI, FPKPA, training exposure, match exposure, and total exposure (training exposure + match exposure) were categorised as above normal (+1 SD above the mean), normal (within 1 SD of the mean), and below normal (- 1 SD below the mean) with respect to the mean value for that risk factor in the cohort. A generalised linear mixed model for binary data with injury/no injury as the dependent variable was used to analyse the associations between the potential risk factors and the risk of acute non-contact lower extremity injury/ankle injury/knee injury. Leg was used as a unit of analysis and team and leg were used as random effects. First, the potential risk factors were analysed using a univariate model. Then, all the variables achieving $P < 0.20$ in the univariate analysis were entered into a multivariate model. For the significant risk factors, ROC curve analysis was performed to establish the AUC, which was used to classify the combined sensitivity and specificity as outstanding (0.90–1), excellent (0.80–0.89), acceptable (0.70–0.79), poor (0.51–0.69) and no discrimination (0.50) (Hosmer, Lemenshow, & Sturdivant, 2013). The paired samples *t* test was used to analyse differences in the mean FPKPA between legs. The mean age of the cohort (15.7 years) was used to divide the players into age categories. The independent samples *t* test was used to analyse differences in FPKPA between older and younger players of the same sex. To compare the mean FPKPA between sexes, a univariate model with age as a covariate was used.

In Study IV, to compare the injured and uninjured subjects, the Mann-Whitney U test was used to test the variables that were not normally distributed (age, height, weight, BMI), the independent samples *t* test was used for the normally distributed variables (right FPKPA, left FPKPA), and the chi-square test was used for the categorical variables (sex). Similarly to Study III, categorical variables were formed based on the continuous variables utilising the cohort mean and SD. Age, height, weight, FPKPA, and FPKPA asymmetry were categorised as above normal, normal and below normal. For the subgroups of boys and girls, the categorised

variables were calculated based on the mean values of each subgroup. BMI was categorised into healthy, low, and overweight based on the cut-off values for adolescents (Cole, Bellizzi, Flegal, & Dietz, 2000; Cole, Flegal, Nicholls, & Jackson, 2007). A generalised linear mixed model for binary data with injury/no injury as the dependent variable was used to analyse the potential risk factors. Leg was used as a unit of analysis and team and leg were used as random effects. The independent samples *t* test was used to investigate the differences in the mean FPKPA between sexes. To analyse the differences in the mean FPKPA between the right and left leg and dominant and non-dominant leg, the paired samples *t* test was used. One-way analysis of variance was used to investigate the differences in the mean FPKPA between age groups.

In all four studies, statistical analyses were performed using SPSS software (IBM SPSS Statistics Version 21 for Windows in Study II, v 23 in Studies I and III, and v 24 in Study IV). In all four studies, the significance level was set at $P < 0.05$.

4.6 Contribution statement

In addition to being the first author and the corresponding author in all of the four manuscripts comprising this doctoral dissertation, the doctoral candidate has also been involved with several other aspects of the PROFITS study and the Sports Injury Prevention Youth Football study

In the PROFITS study, the doctoral candidate was involved with the third year data collection. This included the collection of 3D (not used in this dissertation) and anthropometric data, as well as assisting the study coordinator by contacting the athletes to schedule test sessions, preparing the test sites, and checking baseline questionnaires for inconsistencies. In addition, the doctoral candidate contributed to data management and data preparation, such as calculating exposure times from match records.

In the Sports Injury Prevention Youth Football study the doctoral candidate was involved with the development of the research project. This included significant contributions to the planning, piloting, and managing the test events during the two-year test period. The doctoral candidate contributed to the training of the research assistants performing the field tests, as well as to teaching the study physiotherapists how to collect the injury data. The doctoral candidate carried out most of the single-leg squat tests before the intervention phase began. She distributed, checked, and managed the consent forms together with another

researcher. The doctoral candidate contributed to the coding and cleaning of the baseline questionnaire data as well as the test data. During the intervention phase, the doctoral candidate visited the teams on site to observe training sessions. In addition, she contributed to the education of the coaches of the intervention teams.

The doctoral candidate contributed to the injury registration during the first year of the Sports Injury Prevention Youth Football study. The data from this pilot year is not used in this dissertation. The doctoral candidate did not contribute to the second year injury registration beyond being involved with the recruiting and educating the study physiotherapist prior to the registration began, as it was necessary for the doctoral candidate to be blinded of the injury status during the 2D video analysis.

5 RESULTS

5.1 Adolescent physical activity-related injuries (I)

5.1.1 Subjects

Among the 9,462 subjects, 41% (3,881) were boys and 59% (5,581) were girls. The proportions of boys and girls by age are presented in Figure 8. Proportions of subjects reporting participation in sport club activities, school sports and leisure time PA are presented in Figure 9.

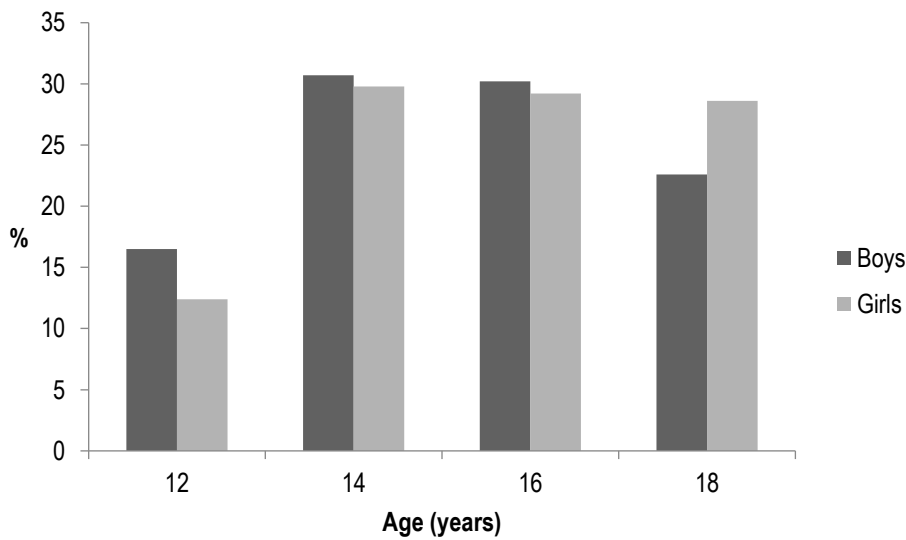


Figure 8. Proportion of boys and girls in each age category.

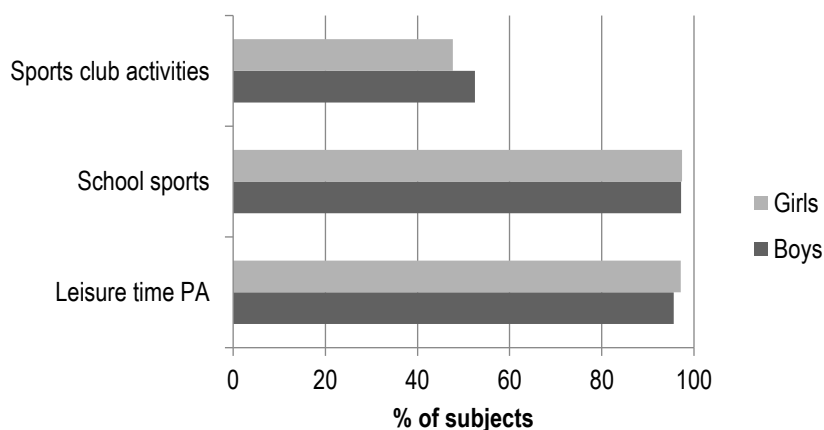


Figure 9. Proportions of subjects participating in sports club activities, school sports (being students), and leisure time physical activity (PA) by sex.

5.1.2 Injury prevalence in sports club activities, school sports, and leisure time PA

Among the subjects reporting PA participation, 32% (95% CI: 31.0–33.0) had sustained at least one PA-related injury during the one-year period. The injury prevalence in sports club activities, school sports, and leisure time PA for boys and girls was 27.5%, 9.8%, and 17.6% and 23.8%, 10.0%, and 13.3%, respectively. Injury prevalence was higher in sports club activities compared to school sports ($P < 0.001$ for boys and for girls) and leisure time PA ($P < 0.001$ for boys and for girls). In leisure time PA, injury prevalence was significantly higher than in school sports for boys ($P < 0.001$) and for girls ($P < 0.001$).

Injury prevalence varied significantly between age groups in sports club activities (boys $P < 0.003$, girls $P < 0.004$), school sports ($P < 0.001$ for boys and for girls), and leisure time PA ($P < 0.001$ for boys and for girls). Among the boys, the injury prevalence in sports club activities was highest among the older (aged 16 and 18 years) subjects (30.8% and 32.3%, respectively). Among the girls, the 14-year-olds had the highest prevalence of sports club injuries (26.7%). In school sports and leisure time PA, the injury prevalence was highest among the younger (aged 12 and 14 years) subjects in both boys and girls. Injury prevalence in the three settings by age group is presented in Figure 10.

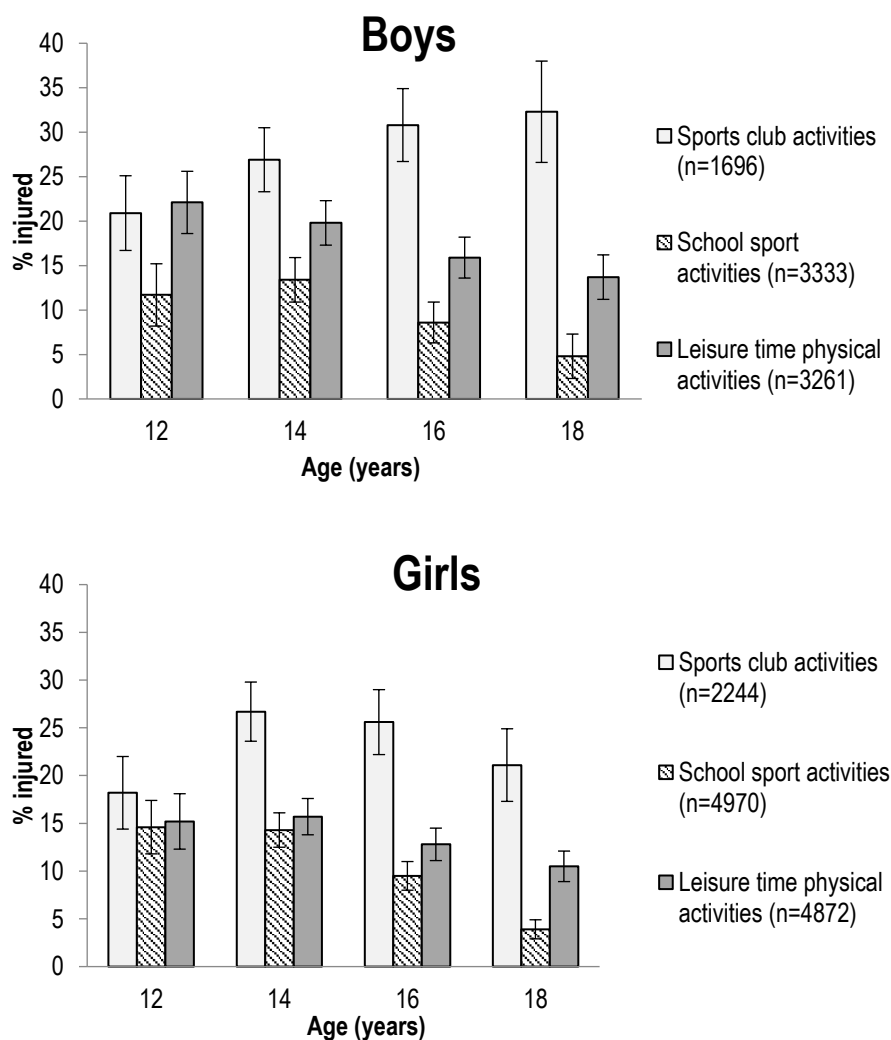


Figure 10. Prevalence of sports club activities, school sports, and leisure time physical activity injuries by age for boys and girls, presented with 95% confidence intervals. Proportions were calculated according to the subjects who reported participation in sports club activities/being students/participating in leisure time PA. From Räsänen et al. 2016, reproduced in accordance with the Creative Commons Attribution licence.

5.1.3 PA participation frequency, intensity, and injury prevalence

Frequency of PA participation was associated with injury prevalence. In sports club activities, subjects participating 2 to 3 times per week had three-fold odds of injury

compared to subjects participating less than once a month (OR 3.1, 95% CI: 2.0–4.6). For subjects participating in sports club activities 4 to 5 times per week or approximately daily, odds ratios were 6.9 (95% CI: 4.5–10.5) and 10.4 (95% CI: 6.7–16.3), respectively.

For leisure time PA, significant association between injuries and participation frequency were detected in subjects participating in leisure time PA at least once per week. Those participating approximately once per week had 1.7 (95% CI: 1.1–2.6) times higher odds of injury compared to those participating less than once a month. The odds of injury increased along with participation frequency, up to 3.1 (95% CI: 2.0–4.7) times among those participating approximately daily.

Exercise intensity, described as sweating and/or getting out of breath during PA, was associated with PA-related injury. Odds of injury were two-fold in subjects reporting moderate intensity (OR 2.2, 95% CI: 1.6–3.2) and four-fold in subjects reporting extensive (OR 4.1, 95% CI: 2.9–5.8) sweating/getting out of breath compared to the reference group reporting no sweating/getting out of breath during exercise.

5.2 Visual assessment of single-leg squat performance (II)

5.2.1 Subjects

A total of 378 players participated in the SLS test. Among them, 248 were female (age 17.7 ± 4.0 years, height 168.2 ± 7.0 cm, weight $62.7 \text{ kg} \pm 8.1 \text{ kg}$, BMI 22.1 ± 2.5) and 129 were male (age 16.6 ± 1.5 years, height 179.4 ± 8.2 cm, weight $70.1 \text{ kg} \pm 10.4 \text{ kg}$, BMI 21.7 ± 2.5). The number of players by sport is presented in Figure 11.

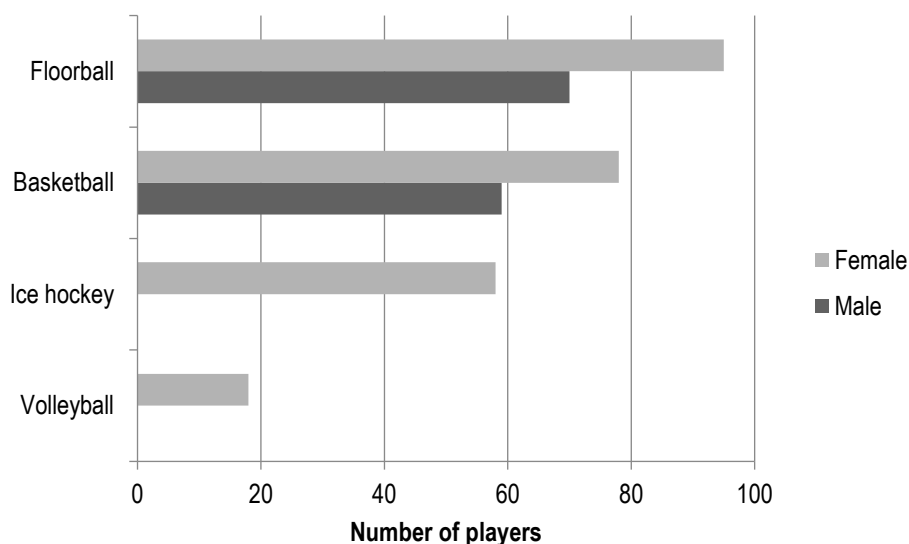


Figure 11. Number of players by sport.

5.2.2 Correlation between visual assessment and 2D video analysis

The proportions of players in the groups based on the visual assessment of knee control are presented in Figure 12. There were significant differences in the mean FPKPA between the groups of good, reduced, and poor performers on the dominant ($P<0.001$) and non-dominant leg ($P<0.001$). The mean values of FPKPA are presented in Table 6. The correlation between the visual assessment and the FPKPA was good for both the dominant and non-dominant leg (0.64 and 0.63, respectively).

Table 6. The frontal plane knee projection angle ($^{\circ}$) mean with standard deviation (SD) and range for the groups based on the visual assessment of knee control

	Visual assessment					
	Good		Reduced		Poor	
	mean (SD)	range	mean (SD)	range	mean (SD)	range
Dominant leg	2.2 (7.3)	-10.1 to 20.2	7.9 (7.6)	-16.2 to 31.0	18.7 (8.1)	-4.0 to 56.9
Non-dominant leg	1.2 (6.4)	-14.1 to 15.2	7.5 (6.5)	-13.8 to 24.1	18.1 (8.7)	-6.0 to 38.8

5.2.3 Intra- and inter-rater reliability

The intra-rater agreement for the physiotherapist's visual assessment was fair for the first-year sample, moderate to good for the second-year sample, and good to very good for the third-year sample. The inter-rater agreement between the physiotherapist's and the non-experienced observer's assessments was fair on the dominant leg ($\kappa=0.32$) and poor on the non-dominant leg ($\kappa=0.16$).

5.3 Knee control and injury risk in young floorball and basketball players (III)

5.3.1 Subjects

Complete data consisting of the FPKPA and prospective 12-month injury data were obtained from 306 players (age 15.7 ± 1.8 years, height 173.3 ± 9.1 cm, weight 64.6 ± 10.0 kg). Among them, 52% were male, 48% were female, 50% played basketball, and 50% played floorball. The dominant leg was the right leg in 68% and the left leg in 29%. Nine players (3%) did not have or could not name a preferred leg. A total of 146 lower extremity injuries were recorded, and 110 players sustained at least one injury during the 12-month follow up. These players did not differ from the 196 uninjured athletes by age, height, weight, BMI, sex, sport, training exposure, match exposure, or match and training exposure.

The ankle was the most commonly injured body part (50% of injuries), followed by the knee (21%). The number of injuries to different lower extremity locations is presented in Figure 13. Only the players who had been free from acute lower extremity injury for the 12 months prior to baseline were included in the lower extremity injury risk factor analysis. Similarly, players had to be free from ankle injury for 12 months before the study to be included in the analysis of ankle injury risk factors and free from knee injury for the knee injury risk factor analysis. Among the 306 players, 155 of them had been free from lower extremity injury and 47 were injured during the follow-up. A total of 207 players had been free of an ankle injury and 41 of them sustained at least one ankle injury. In addition, 269 players had been free from knee injury and 18 of them sustained a knee injury.

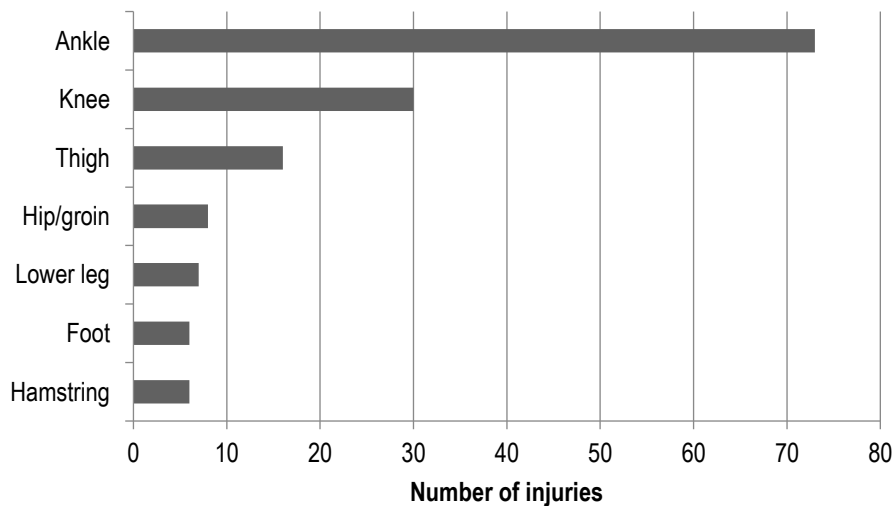


Figure 12. Locations of lower extremity injuries.

5.3.2 Lower extremity injury risk factors

In the univariate analysis of lower extremity injury risk factors, a high FPKPA ($>23.8^\circ$) during the SLS and a low match exposure (<3.9 hours) achieved $P<0.20$, and the categorical variables of FPKPA and match exposure were then entered into the multivariate model. In the multivariate analysis, high FPKPA ($>23.8^\circ$) was a significantly associated with lower extremity injury (adjusted OR 2.67, 95% CI: 1.23 to 5.83, $P=0.01$). The odds ratios for the univariate analysis and the adjusted odds ratios for the multivariate analysis are presented in Table 7.

In the univariate analysis of acute ankle injury risk factors, only high FPKPA ($>23.8^\circ$) achieved $P<0.20$ and therefore multivariate analysis was not performed. Athletes displaying a high FPKPA ($>23.8^\circ$) during the SLS were 2.4 times more likely to sustain an ankle injury than were athletes in the reference group (OR 2.37, 95% CI: 1.13 to 4.98, $P=0.02$).

For the knee injury risk factor analysis, only higher age (>17.5 years) achieved $P<0.20$ in the univariate analysis, and no multivariate analysis was performed. Age was not a significant risk factor for acute knee injury (OR 2.22, 95% CI: 0.89 to 5.53).

Table 7. The odds ratios (OR) for potential risk factors for lower extremity injuries presented with 95% confidence intervals (CIs)

UNIVARIATE ANALYSIS	OR	95% CI	P value
Categorical variables			
Basketball	1		
Floorball	0.97	0.52-1.79	0.92
Female	1		
Male	1.08	0.58-1.99	0.81
Age, intermediate	1		
Age, low (<13.9 years)	1.58	0.72-3.50	0.26
Age, high (>17.5 years)	1.35	0.55-3.35	0.51
Height, intermediate	1		
Height, low (<164.2 cm)	0.81	0.35-1.87	0.62
Height, high (>182.4 cm)	0.91	0.37-2.22	0.83
Weight, intermediate	1		
Weight, low (<54.7 kg)	0.71	0.28-1.79	0.46
Weight, high (>74.6 kg)	0.51	0.17-1.50	0.22
BMI, intermediate	1		
BMI, low (<19.0)	0.99	0.42-2.30	0.97
BMI, high (>23.9)	1.14	0.49-2.69	0.76
FPKPA, intermediate	1		
FPKPA, low (<2.7°)	1.12	0.43-2.90	0.82
FPKPA, high (>23.8°)	2.55	1.18-5.51	0.02 *
Training exposure, intermediate	1		
Training exposure, low (<162.4 h)	1.33	0.58-3.02	0.50
Training exposure, high (>346.0 h)	0.83	0.30-2.28	0.71
Match exposure, intermediate	1		
Match exposure, low (<3.9 h)	0.44	0.13-1.49	0.19 *
Match exposure, high (>15 h)	0.69	0.29-1.65	0.41
Match and training exposure, intermediate	1		
Match and training exposure, low (<169.6 h)	1.19	0.51-2.78	0.70
Match and training exposure, high (>357.7 h)	0.81	0.29-2.23	0.68
Continuous variables			
Age (years)	1.04	0.87-1.24	0.67
Height (cm)	1.00	0.97-1.04	0.85
Weight (kg)	1.00	0.97-1.04	0.86
BMI (kg/m ²)	1.01	0.90-1.14	0.87
FPKPA (°)	1.01	0.98-1.05	0.38
Training exposure (h)	1.00	1.00-1.00	0.95
Match exposure (h)	0.99	0.94-1.05	0.82
Match and training exposure (h)	1.00	1.00-1.00	0.94
MULTIVARIATE ANALYSIS			
FPKPA, high (>23.8)	2.67	1.23-5.83	0.01 †

* Variables with a P value <0.20 in the univariate analysis were entered into the multivariate model.

† Only variables with a P value <0.05 in the multivariate model are presented.

5.3.3 Sensitivity and specificity analyses

ROC curve analyses were performed to determine the value of the FPKPA as a screening tool for acute lower extremity and ankle injury. The AUCs for lower extremity injury and ankle injury were 0.59 and 0.58, respectively, which indicate poor combined sensitivity and specificity. As is presented in Figure 14 for lower extremity injuries, the FPKPA values overlap between the injured and uninjured lower extremities.

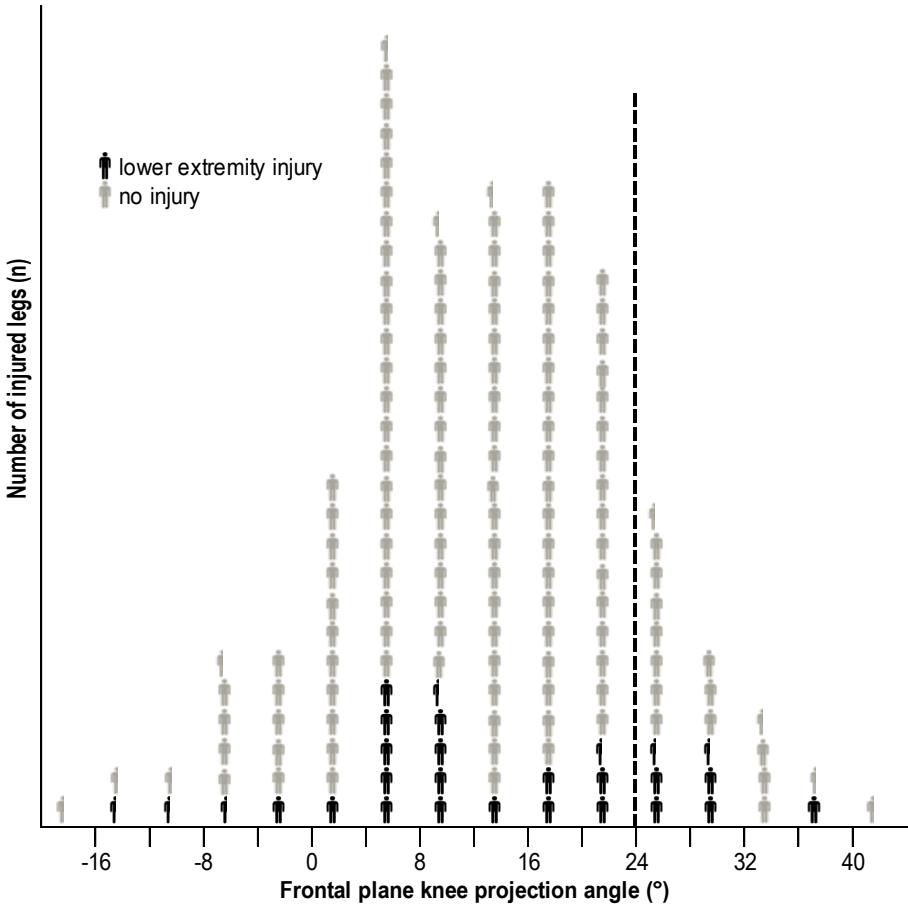


Figure 13. Distribution of injured and uninjured lower extremities by frontal plane knee projection angle. The vertical line represents the cut-off point for the high frontal plane knee projection angle ($>23.8^{\circ}$). From Räsänen et al. 2018, reproduced in accordance with the Creative Commons Attribution licence.

5.3.4 Age, sex, and side-to-side differences

The age, sex, and side-to-side differences in the FPKPA have not been published previously. The mean FPKPA was $12.1 \pm 11.4^\circ$ for males and $14.5 \pm 9.4^\circ$ for females. There were no significant differences in the FPKPA between sexes when adjusted for age. Mean FPKPA did not differ significantly between the dominant and non-dominant leg in any of the analysed groups (Table 8). Among males, the left leg FPKPA was significantly smaller than that of the right. Among males, the older athletes displayed significantly smaller FPKPAs compared with the younger athletes. The differences were significant on the right ($P=0.006$), left ($P=0.001$), dominant ($P=0.001$), and non-dominant ($P=0.01$) leg. Among females, there were no differences in the mean FPKPA between the older and younger athletes. Between male and female players, there were significant differences in the FPKPA on the left ($P=0.005$) and the non-dominant leg ($P=0.03$) among the older players.

Table 8. The mean frontal plane knee projection angle (FPKPA) for the right, left, dominant, and non-dominant leg by sex and age group

Sex and age group	FPKPA right	FPKPA left	P value	FPKPA dominant	FPKPA non-dominant	P value
Male	13.9 (11.9)	10.3 (10.6)	<0.001	12.8 (11.9)	11.4 (10.8)	0.13
≤ 15.7 years	17.4 (10.4)	13.5 (10.1)	0.034	16.1 (11.1)	14.8 (9.7)	0.48
> 15.7 years	12.6 (12.1)	9.2 (10.6)	0.001	11.6 (12.0)	10.2 (10.9)	0.18
Female	14.4 (9.3)	14.5 (9.6)	0.97	14.3 (8.9)	14.1 (9.4)	0.79
≤ 15.7 years	14.6 (9.2)	15.0 (10.0)	0.76	14.9 (8.9)	13.7 (9.3)	0.26
> 15.7 years	14.2 (9.4)	13.9 (9.0)	0.75	13.6 (9.0)	14.5 (9.5)	0.36

5.4 Knee control and injury risk in youth football players (IV)

5.4.1 Subjects

A total of 558 players (445 boys, 113 girls) participated in the baseline SLS and completed the injury surveillance. The basic characteristics of the players by sex and age group are presented in Table 9. The dominant leg, defined as the preferred leg for kicking the ball, was the right leg for 88% and the left leg for 12%. Two players did not name a preferred leg. During the follow-up, 285 acute lower

extremity injuries were registered, 142 (50%) of which were non-contact injuries. Among the 558 players, 37% (n=205) sustained at least one lower extremity injury.

Table 9. Mean (SD) values for basic characteristics by sex and age group

Age group	n	Height (cm)	Weight (kg)	BMI	Playing football (years)	FPKPA (°)
Boys	445	151.6 (9.9)	41.1 (8.7)	17.7 (1.9)	6.5 (1.7)	16.5 (12.6)
U11	117	143.3 (6.5)	34.9 (5.3)	16.9 (1.6)	5.1 (1.2)	17.6 (13.5)
U12	105	148.5 (6.5)	38.0 (5.1)	17.2 (1.5)	6.1 (1.2)	17.5 (13.5)
U13	116	154.0 (7.8)	43.3 (6.6)	17.8 (1.8)	6.8 (1.5)	17.0 (12.0)
U14	107	161.7 (8.3)	49.9 (9.2)	18.9 (2.2)	8.0 (1.3)	14.2 (11.5)
Girls	113	151.7 (9.2)	41.6 (7.7)	17.9 (1.7)	5.3 (1.6)	15.4 (10.7)
U11	26	140.5 (4.1)	33.1 (3.9)	16.7 (1.5)	4.2 (1.5)	15.0 (9.8)
U12	32	149.1 (6.4)	39.9 (5.8)	17.9 (1.4)	5.0 (1.0)	19.2 (11.3)
U13	31	157.3 (5.9)	45.6 (5.9)	18.3 (1.6)	5.7 (1.5)	14.2 (11.4)
U14	24	159.6 (5.9)	47.8 (5.3)	18.7 (1.5)	6.2 (1.8)	12.2 (8.3)

Most of the injuries were minor, causing 1 to 3 days of absence from training and/or match play (Figure 15). The ankle was the most commonly injured body part (32% of injuries), followed by the knee (20%) (Figure 16). The dominant leg was injured in 51% and the non-dominant leg in 48% of the injury cases. In three slight injuries, the player was unable to identify which leg had been injured.

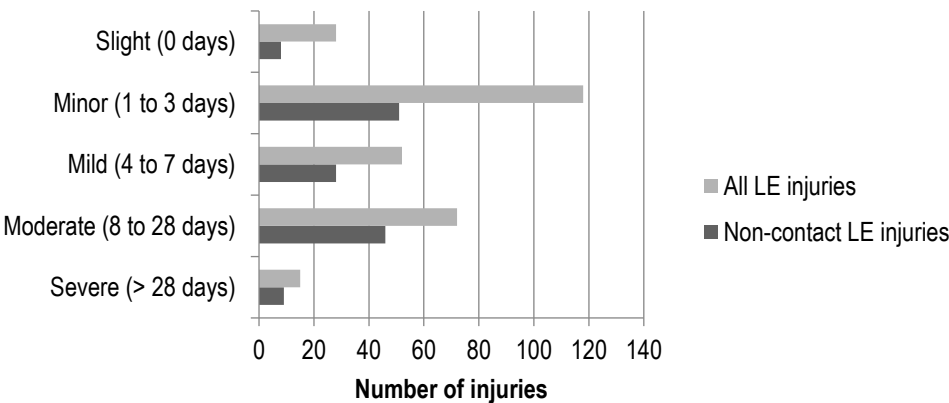


Figure 14. Severity of lower extremity injuries. From Räisänen et al. in press.

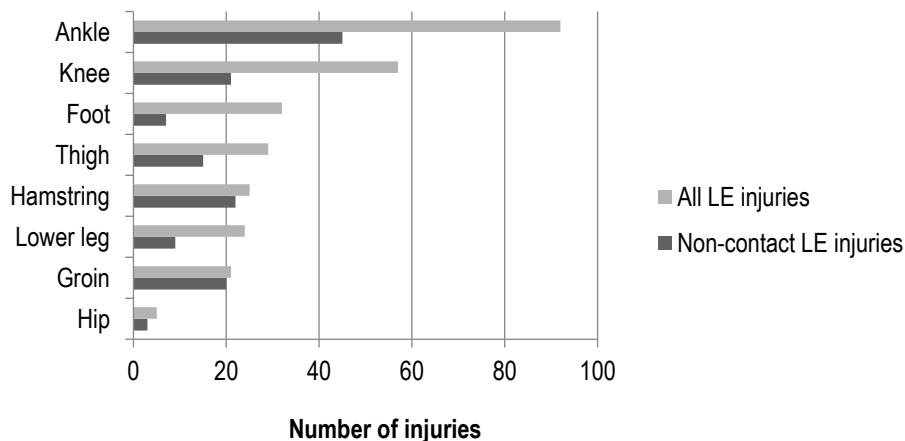


Figure 15. Locations of lower extremity injuries. From Räsänen et al. in press.

In the baseline SLS test, 40 players were unable to perform enough valid squats on either leg and an additional 92 players only performed the required number of squats on one leg. When comparing the injured players to the uninjured, there were no significant differences in the mean age, height, weight, BMI, number of years playing football, or the proportion of boys and girls.

5.4.2 Lower extremity injury risk factors

The intrinsic factors analysed in the univariate analysis are presented in Table 10. Based on the univariate analysis, the categorical variables of weight, BMI, and continuous height were entered into a multivariate model. None of the analysed variables were associated with lower extremity injuries (Table 11).

To examine the lower extremity risk factors in boys, categorical height, weight, and continuous age were entered into the multivariate model. None of the analysed variables were associated with lower extremity injuries. For the girls, none of the analysed intrinsic factors achieved $P < 0.20$ in the univariate analysis.

Table 10. Univariate analyses of the potential risk factors for acute lower extremity injuries presented with 95% confidence intervals (CIs)

Intrinsic factors	n (injured)	OR	95% CI	P value
Categorical variables				
Boy	884 (183)	1		
Girl	226 (47)	0.94	0.63 to 1.40	0.75
Age, intermediate	650 (133)	1		
Age, low (<10.8 years)	236 (46)	0.93	0.64 to 1.35	0.70
Age, high (>13.2 years)	224 (51)	1.13	0.78 to 1.63	0.51
Height, intermediate	726 (152)	1		
Height, low (<142.3 cm)	186 (33)	0.81	0.53 to 1.23	0.32
Height, high (>161.1 cm)	172 (40)	1.13	0.76 to 1.68	0.56
Weight, intermediate	702 (148)	1		
Weight, low (<33.9 kg)	204 (34)	0.75	0.49 to 1.13	0.16 *
Weight, high (>49.3 kg)	178 (43)	1.17	0.79 to 1.73	0.43
BMI, healthy	984 (211)	1		
BMI, low	58 (7)	0.53	0.24 to 1.19	0.12 *
BMI, overweight	40 (7)	0.83	0.36 to 1.92	0.67
FPKPA, intermediate	622 (126)	1		
FPKPA, low (<4.0°)	154 (36)	1.19	0.78 to 1.82	0.42
FPKPA, high (>28.4°)	163 (34)	1.03	0.67 to 1.58	0.90
Able to perform valid SLS	938 (196)	1		
Unable to perform valid SLS	162 (31)	0.90	0.59 to 1.38	0.63
FPKPA asymmetry, intermediate	574 (124)	1		
FPKPA asymmetry, low (<2.6°)	132 (25)	0.86	0.53 to 1.39	0.54
FPKPA asymmetry, high (>18.8°)	148 (28)	0.84	0.53 to 1.33	0.46
Continuous variables				
Age (years)	1110 (230)	1.08	0.96 to 1.23	0.22
Height (cm)	1084 (225)	1.01	1.00 to 1.03	0.15 *
Weight (kg)	1082 (225)	1.02	1.00 to 1.03	0.08 *
BMI	1082 (225)	1.05	0.98 to 1.14	0.19 *
FPKPA (°)	938 (196)	1.00	0.99 to 1.01	0.95
FPKPA asymmetry (°)	898 (164)	1.00	0.98 to 1.03	0.67

* P<0.20

n refers to the number of legs in the analysis

Table 11. Multivariate analyses of the potential risk factors for all acute lower extremity injuries for all subjects and the subgroups of boys and U13–U14 age groups presented with 95% confidence intervals (CIs)

Intrinsic factors	n (injured)	OR	95% CI	P value
All subjects				
Height (cm)	1084 (225)	1.00	0.96 to 1.04	0.96
Weight (kg)	1082 (225)	1.02	0.97 to 1.06	0.46
BMI, healthy	984 (211)	1		
BMI, low	58 (7)	0.60	0.25 to 1.39	0.23
BMI, overweight	40 (7)	0.66	0.245 to 1.74	0.40
Boys				
Height, intermediate	614 (128)	1		
Height, low (<141.7 cm)	128 (19)	0.86	0.44 to 1.68	0.65
Height, high (>161.5 cm)	126 (31)	1.13	0.59 to 2.14	0.72
Weight, intermediate	636 (133)	1		
Weight, low (<32.4 kg)	104 (14)	0.65	0.31 to 1.34	0.24
Weight, high (>49.8 kg)	128 (31)	1.10	0.58 to 2.07	0.79
Age (years)	884 (183)	1.01	0.85 to 1.21	0.89

Only the variables achieving $P < 0.20$ in the univariate analyses were analysed.

n refers to the number of legs in the analysis

5.4.3 Non-contact lower extremity injury risk factors

In the univariate analysis of potential non-contact lower extremity risk factors low BMI and high FPKPA asymmetry achieved $P < 0.20$. In the multivariate analysis, neither of the factors was significantly associated with non-contact lower extremity injuries. For the boys, low BMI and high FPKPA asymmetry achieved $P < 0.20$ in the univariate analysis. For the girls, weight and ability to perform a valid SLS test were entered into the multivariate model but were not associated with the risk of non-contact lower extremity injury.

5.4.4 Age, sex, and side-to-side differences in the FPKPA

There were no significant differences in the mean FPKPA between boys and girls. There were significant differences in the FPKPA between age groups among boys ($F = 3.09$, $P = 0.03$) and girls ($F = 4.22$, $P = 0.006$). Among boys, the mean FPKPA decreased as age increased. Among girls, the greatest mean FPKPA was measured in the U12 age group. The oldest girls (U14) demonstrated the best frontal plane

knee control with a mean FPKPA of $12.2 \pm 8.3^\circ$. The mean FPKPAs by age and sex are presented in Table 9.

There were significant differences in the mean FPKPA between the right and left leg and between the dominant and non-dominant leg in boys and girls. In both sexes, the FPKPA was greater on the right leg compared to the left ($P < 0.001$ for boys and girls) and greater on the dominant compared to the non-dominant leg ($P < 0.001$ for boys, $P = 0.001$ for girls). When further analysed according to age group, the differences were significant in all age groups among boys and U11 girls.

6 DISCUSSION

6.1 Physical activity-related injuries as a public health issue

According to the present findings, every third adolescent participating in sports club activities was injured during a 12-month period, and the prevalence of injuries increased along with the frequency and intensity of activity. Healthy life years and valuable training time are lost due to injuries during critical developmental years (Rumpf & Cronin, 2012).

6.1.1 Injury prevalence in different settings

It has been previously established that physical activity is the leading cause of adolescent injuries in many developed countries (Michaud et al., 2001). The purpose of Study I was to increase our understanding of the settings in which PA-related injuries occur. The results show that injury prevalence was higher in sports club activities compared to school sports and leisure time PA. Furthermore, the injury prevalence in leisure time PA was higher than prevalence in school sports.

A comparisons of these results to those of previous studies is somewhat limited by different data collection methods. A previous study on 9-, 12-, and 15-year-old Swedes utilised a 3-month recall period (Sundblad, Saartok, Engström, & Renström, 2005). Injury was defined as a traumatic injury that caused an interruption in PA participation and the need for medical attention by an adult. Most injuries occurred during leisure time PA (29%), followed by physical education classes (25%), and organised sports (19%). The remainder of the injuries occurred during break (16%), travel to or from school (3%), or in unknown circumstances (8%). More injuries were reported by girls than by boys in physical education classes, and the oldest students, who were in the 9th grade, reported more injuries from sports practices compared to the younger subjects. Overall, equal proportions of boys and girls reported injuries. In a study on 10- to 12-year-olds, injury incidence was highest in sports (0.66 injuries/1000 hours of participation), followed by physical education classes (0.50 injuries/1000 h), and

leisure time PA (0.39 injuries/1000 h) (Verhagen, Collard, Chin A Paw, & van Mechelen, 2009). Among a slightly younger cohort of 6- to 12-year-olds, injury incidence was highest in sports (1.57 injuries/1000 h), followed by leisure time PA (0.57 injuries/1000 h) and physical education classes (0.14 injuries/1000 h) (Jespersen et al., 2015). Even though there discrepancy between the studies on in which environment the injury prevalence or incidence is highest, we can gather that the injury prevalence in sports club activities is high. However, it must be noted that due to the large proportion of adolescents participating in leisure time PA, the absolute number of leisure time PA injuries is high (Nauta, Martin-Diener, Martin, van Mechelen, & Verhagen, 2015). Furthermore, given that physical education in schools is mandatory in the Finnish educational system, it should be fundamentally safe for the pupils. More effective injury prevention efforts are needed in all of the three PA settings.

6.1.2 Physical activity promotion and injury prevention

PA promotion is an important health promotion tool that is of great value to public health. However, there is a need to promote safe physical activity. While the harm caused by injuries may be very small at the population level in relation to the significant benefits of PA, ignoring the risk of injuries in PA promotion does not help to prevent injuries or increase the safety of PA (Verhagen et al., 2015). Annually, up to 8% of adolescents drop out of PA participation due to injury or fear of injury (Grimmer, Jones, & Williams, 2000). In addition, the long-term consequences of PA-related injuries need to be considered: adolescents dropping out due to injury lose the health benefits engendered by continuous participation.

The present findings indicate that the odds of injury increase along with frequency of participation and intensity. As regular and more frequent participation is promoted, efforts need to be made to enhance the safety of the participation. Moreover, it has been previously reported that a low level of PA is significant risk factor for PA-related injuries among 9- to 12-year-olds (Bloemers et al., 2012). If an adolescent who is not so interested in PA becomes injured, that could potentially give rise to a very negative attitude towards PA and lead to dropping out completely. To reduce the adverse effects of PA participation, it is very important that PA promotion also focuses on injury prevention (Bloemers et al., 2012; Finch & Owen, 2001; Verhagen et al., 2015).

6.1.3 Importance of surveillance and monitoring

One purpose of Study I was to update the knowledge on adolescent PA-related injury prevalence in Finland. Since 1977, the AHLS has been used to monitor many adolescent health and health-related behaviours, such as smoking and alcohol consumption. PA-related injuries were a part of the initial survey in 2007 and were included again in 2009 and 2013.

Injury surveillance is the first step toward injury prevention in the Translating Research into Injury Prevention framework (Finch, 2006). In Finland, new monitoring methods are necessary to collect reliable information regarding injury incidence. It has been shown previously that injury prevention reduces injury-related costs (Lacny et al., 2014; Marshall et al., 2016). Before the benefits of injury prevention efforts can be measured on national level, a national injury surveillance system is needed. Monitoring for injuries at the population level is a challenge (Finch et al., 2017), and surveillance of PA-related injuries should be incorporated into public health strategies (Finch & Owen, 2001). In Finland, the importance of adolescent PA-related injury prevention is acknowledged in the national action plan of injury prevention, but surveillance and monitoring methods have not been established (Markkula & Öörni, 2010).

For surveillance to provide sufficient sports injury data, multiple strategies of continuous data collection are needed. One possible level is the modification of coding in hospital emergency departments that allows sports to be identified as a cause of injury (Finch et al., 2014). With such coding, the hospital registry data could be used to assess the role of sports participation as a cause of injury, which would allow the public health burden to be estimated. Furthermore, by recording which sport the patient was participating in, it would be possible to assess the role of different sports and evaluate the need for injury prevention methods. However, emergency department visits only represent one aspect of the sports injury problem. In addition, the coding systems do have their weaknesses: the coding can be considered overly time-consuming by physicians and the same injuries can be coded differently (Rae, Britt, Orchard, & Finch, 2005). Therefore, other injury monitoring strategies are also needed.

National sports federations should be interested in injury prevention and continuous injury data collection, as it would provide important information regarding injury incidence in the sport. Furthermore, when injury prevention methods, such as changes in rules or safety equipment, are introduced, the data could be used to quantify the change in injury incidence. However, since sports

injury records are medical records, the requirements to ensure ethical use are very extensive. In Norway, an online questionnaire has been used for the injury and illness surveillance of Olympic and Paralympic athletes (Clarsen, Rønsen, Myklebust, Flørenes, & Bahr, 2014).

6.1.4 Injury prevention

Previous studies have shown that it is possible to prevent adolescent PA-related injuries. Simply participating in sport club activities does not seem to provide the adolescents with the adequate movement control skills to correct faulty movement patterns. In a study on adolescent basketball and floorball players, basketball players did not demonstrate better knee control in a jump-landing task compared to floorball players, even though their sport includes jumping and landing (Leppänen et al., 2016). In the sport club environment, injury prevention exercise programs (IPEPs) have been shown to be effective in many team sports (Emery, Roy, Whittaker, Nettel-Aguirre, & van Mechelen, 2015; Rössler et al., 2014). Use of an IPEP has also been shown to produce good results in the school environment, although the results are still limited (Richmond, Kang, Doyle-Baker, Nettel-Aguirre, & Emery, 2016). However, the adoption and regular use of IPEPs in sports are challenging, and further studies on the optimal implementation strategies are needed (Lindblom, Carlford, & Hägglund, 2018; Lindblom, Waldén, Carlford, & Hägglund, 2014). In leisure time PA, injuries can be prevented by providing safe environments (Embree et al., 2016) and by non-legislative interventions regarding bicycle helmet use (Royal, Kendrick, & Coleman, 2007), for example. In conclusion, it is possible to prevent adolescent PA-related injuries.

6.2 Single-leg squat as a tool to assess frontal plane knee control

The results of Study II demonstrate that it is possible to detect differences in frontal plane knee control during the SLS using visual assessment. In addition, the results indicate that for an experienced observer, the intra-rater reliability of the visual assessment is good to very good.

6.2.1 Visual assessment of knee control

Significant differences in FPKPA between the SLS performances rated to be “good”, “reduced”, or “poor” were found. The FPKPA increased from the mean value of 1.2° to 2.2° in the good performers to 18.1° to 18.7° in the poor performances. Overall, the correlation between the visual assessment and the FPKPA was good. The results of this study are in accordance with a previous study, in which the same 3-point graded scale was used and significant differences between the three groups were detected (Stensrud et al., 2010). Harris-Hayes and colleagues (2014) also utilised a 3-point scale for knee control assessment, but with different criteria. They concluded that the agreement between the visual assessment and the 2D method is excellent. Using electromyography (EMG) to analyse differences in performance between the groups formed by visual assessment, Crossley and colleagues (2011) demonstrated that the “poor” performances differed from the “good” according to muscle activation patterns. The good performers had significantly earlier onset timing of the anterior gluteus medius and posterior gluteus medius compared to the poor performers. They concluded that the visual assessment may be utilised to identify individuals with hip muscle dysfunction.

The results indicate that the visual assessment of knee control can be a useful tool to identify athletes with reduced knee control in the field setting. From a practical point of view, the visual assessment gives a crude estimate of knee control that may enable clinicians to determine whether the athlete might benefit from exercises aimed to improve knee control.

6.2.2 Intra- and inter-rater reliability

The intra-rater reliability between the initial assessment during the test and the re-assessment from the video image was calculated separately for each of the three years of testing. The kappa value increased from fair during the first year to good to very good during the third year. These results underline the importance of the observer’s experience, which further supports the findings of previous studies (Weeks et al., 2012; Whatman et al., 2012). Weeks and colleagues (2012) reported excellent intra-rater reliability for the experienced observers and good for the novice. The novice observers focused on the knee and did not consider the hip movement in their rating unlike the experienced observers. In the present study, inter-rater reliability during the third year for the more experienced and novice

observers was poor to fair. This is slightly lower than that reported in previous studies (Crossley et al., 2011; Whatman et al., 2012, 2013).

6.2.3 2D analysis of knee control in comparison to the 3D analysis

The main advantages of the 2D movement analysis compared to the 3D method are the ease of use and lower costs. The 2D analysis can be performed in a field setting with minimal equipment, since it requires only a video camera to capture the kinematics and a computer to calculate the FPKPA. For the 3D analysis, more equipment is needed, such as several high-speed cameras. The 3D data is therefore typically captured in a laboratory setting, as it is not as easily transported and set up as the 2D equipment. The 3D method is also more time consuming than the 2D method, which also contributes to the higher cost of the analysis. The value of the 3D method is that three dimensions are measured at once, instead of two. In the SLS performance, 3D analysis allows for the measurement of the knee flexion angle, which cannot be measured using the one-camera 2D method. From the 3D data, it is also possible to analyse the joint rotations, which is not possible in 2D. In the case of the SLS, quantifying the role of hip rotations in the frontal plane knee motion is of interest.

In previous studies on the SLS, both the 3D (Ageberg et al., 2010; Baldon et al., 2011; Claiborne et al., 2006; Graci & Salsich, 2015; Hollman et al., 2014; Horan et al., 2014; Mauntel et al., 2014; Weeks et al., 2012; Willson & Davis, 2008) and 2D (Bittencourt et al., 2012; DiMattia et al., 2005; Harris-Hayes et al., 2014; Herrington, Munro, & Comfort, 2015; Herrington, 2014; McLean et al., 2005; Munro et al., 2012; Stensrud et al., 2010; Stickler et al., 2015) movement analysis methods have been used. The 3D studies on SLS have been small, ranging from 20 to 41 subjects. For a prospective injury risk factor study, a much larger cohort is needed. Previously, two prospective studies investigating the role of knee control as an injury risk factor utilised the 3D analysis method (Hewett et al., 2005; Leppänen et al., 2017) to analyse vertical drop jump performances. It is possible that large cohort studies utilising 3D analysis could become more common in the future, as the cost of the technology decreases. However, since field-based testing makes it easier to recruit participants, it is possible that prospective risk factor studies could utilise the 2D method, while the 3D method could be used in the laboratory to further analyse the findings. For example, the finding of this dissertation that a large FPKPA during the SLS is associated with injuries among

young basketball and floorball players could be further analysed in 3D: for example, a sample of athletes presenting large FPKPA in SLS could be analysed in a 3D laboratory to quantify the joint angles of the SLS. This could enhance our understanding of which joint motions contribute most significantly to poor knee control.

In the SLS test procedure utilised in this doctoral dissertation, the 90° knee flexion angle requires substantial degree of hip flexion. One limitation of this procedure is that the ASIS markers are not always visible at the lowest point of the SLS owing to the combination of hip flexion and trunk forward lean. It may also be related to the body composition or size of the athlete: fat in the abdominal area can obscure the markers when the athlete squats to 90° knee flexion. However, this is a limitation not only in the 2D but also in the 3D method. In the 3D method, each marker has to be visible to at least two cameras at any given point in the movement. Therefore, non-visible markers create a gap in the 3D data. When considering which method to use, the limitations of that both methods must be taken into account.

6.3 Reduced knee control as a lower extremity injury risk factor

In Studies III and IV, the aim was to investigate whether frontal plane knee control during the SLS is associated with lower extremity injuries among young team sport athletes. In Study III, an increased FPKPA during the SLS was associated with higher odds of acute lower extremity injury and acute ankle injury. In Study IV, significant associations between the FPKPA and lower extremity injuries were not detected. To our knowledge, these are the first two prospective risk factor studies investigating the association between the FPKPA and lower extremity injuries.

6.3.1 Frontal plane knee control as a lower extremity injury risk factor

Due to the lack of prospective studies on the SLS, comparisons are limited to studies applying other movement control tests. Utilising the VDJ, Hewett and colleagues (2005) established that among female high school athletes, subjects sustaining an ACL injury during the follow-up demonstrated a 2.5-times greater knee abduction moment upon landing compared to uninjured subjects. In young female floorball and basketball players, Leppänen and colleagues (2017) did not

detect associations between knee control in the VDJ and ACL injuries. In female football players, low normalised knee separation during the VDJ has been associated with a higher risk of acute lower extremity injuries (O’Kane et al., 2015). While the studies on frontal plane knee control in adolescent athletes are not in agreement, there are indications that reduced knee control may increase the risk of acute lower extremity in young team sport athletes.

Reduced knee control during the SLS is associated with reduced hip abductor strength (Crossley et al., 2011). Individuals with reduced frontal plane knee control utilise a hip adductor dominant movement strategy during the SLS, as indicated by their lower gluteus medius to hip adductor and gluteus maximus to hip adductor ratios (Mauntel et al., 2013). The gluteus medius is an important pelvic stabiliser, and adequate gluteus medius strength is required for good frontal plane knee control. Therefore, athletes demonstrating reduced knee control during the SLS should add gluteus medius strengthening to their training. Other strength measurements associated with reduced frontal plane knee control include lower knee flexion and extension (Claiborne et al., 2006), trunk side flexion (Stickler et al., 2015), and hip external rotation strength (Willson et al., 2006). In addition to strength measurements, hip joint stiffness may contribute to frontal plane knee control (Bittencourt et al., 2012). The combination of increased passive hip internal rotation ROM and reduced hip abductor strength contributes to a greater FPKPA.

Knee valgus does not refer to a simple motion, but instead to a combination of various lower extremity motions. Knee valgus may result from femoral adduction and tibial abduction, and there may be concomitant tibial and/or femoral rotations, tibial translation, and ankle eversion (Hewett et al., 2005; Powers, 2003; Quatman et al., 2010). The same FPKPA can arise from very different movements. Nilstad and colleagues (2015) explored the degree of which anatomical characteristics, knee laxity, and muscle strength can explain knee valgus during landing in female football players. Only 11% of the variance in knee valgus could be explained by their model, and further studies are needed to better elucidate the factors associated with knee valgus, since this knowledge could be used to design better training programs for knee control.

The risk of sports injury increases with age, and the risk of injury is higher among the adolescents over 13 years than among the younger adolescents (Emery, 2003). Therefore, it is more difficult to identify injury risk factors among the younger adolescents. During adolescence, knee control seems to improve with age: in Study IV, the oldest players displayed the smallest mean FPKPA, indicating the least valgus movement during the SLS. It is possible that poor frontal plane knee

control becomes a risk factor with increasing age. As size and strength increase with age, greater loads affect the joints and therefore greater valgus can be more problematic.

The lack of association between the FPKPA and future injuries in Study IV does not mean that knee control training is not important among younger adolescents. On the contrary, it seems relevant to start using IPEPs before the injury risk begins to increase with age. The IPEPs are often designed to be used as a warm-up and from a practical stand point, it makes sense to start learning proper warm-up techniques at a young age (Froholdt, Olsen, & Bahr, 2009).

6.3.2 Improving knee control and physical performance

Acknowledging the need for further information on the factors contributing to knee valgus, there are indications that improving knee control requires increases in hip muscle strength and neuromuscular patterns. Furthermore, if ankle dorsiflexion ROM is limited, it should be addressed to allow the tibia to move forward during knee flexion in athletic tasks (Dill et al., 2014; Lima et al., 2018). Teaching correct movement strategies has been shown to yield improvements in knee control in collegiate female athletes (Mizner et al., 2008). Among adult females, significant improvements in knee control were measured in both the hip muscle strengthening group and technique training group (Watson et al., 2017).

Knee control training can also provide performance gains. It has been shown that among young football players, trunk stabilisation training improves measures of physical performance (Hoshikawa et al., 2013). In addition, other neuromuscular training programs have shown that improved knee control is not the only benefit and that the training also improves performance measures (Chappell & Limpisvasti, 2008; Distefano et al., 2010; Kilding, Tunstall, & Kuzmic, 2008; Noyes, Barber-Westin, Smith, & Campbell, 2011). In contrast, three studies on adolescent female football players reported no effect on performance tests after IPEP intervention (Lindblom, Waldén, & Häggglund, 2012; Steffen, Bakka, Myklebust, & Bahr, 2008; Vescovi & VanHeest, 2010).

Even though injury prevention is important for both public and individual health, preventing future injuries is not necessarily of interest to young athletes, though improving their athletic performance usually is. In efforts to increase implementation and compliance with IPEPs, it may be useful to emphasise the connection to potential performance enhancements and to develop IPEPs that,

both reduce injury risk and improve performance. However, further studies on this topic are needed.

6.4 The 2D analysis of the single-leg squat as a screening test

6.4.1 The predictive value of FPKPA

In Study III, significant associations between the FPKPA and acute lower extremity injuries and acute ankle injuries were detected. To examine the predictive value of the FPKPA, a ROC curve analysis was performed. The area under the curve (AUC) was 0.59 for lower extremity injuries and 0.58 for ankle injuries, which can be interpreted as poor combined sensitivity and specificity. The obstacle is the overlapping FPKPA between the injured and uninjured players. The test is unable to separate two distinctly different groups, which seems to be the issue with all potential screening tools (Bahr, 2016a). For a screening test to accurately identify the athletes who are likely to become injured, high sensitivity is essential. In previous studies on adolescent athletes, highest sensitivity values have been reported for LESS at 86% (Padua et al., 2015), FMSTTM at 78% (Chalmers et al., 2017), knee valgus displacement at 75% (Holden et al., 2017), and knee abduction moment at 73% (Hewett et al., 2005). However, none of these results have been repeated in other cohorts. The FPKPA is less sensitive than the previously studied screening tests, and the present findings indicate that the 2D analysis of the single-leg squat is not predictive of injury.

6.4.2 The practical value of movement control tests

It has been previously suggested that one goal of sports injury research is to develop and validate screening tools, that can be used to identify high-risk athletes (Shultz et al., 2010). Since then, several studies on this topic have been published, some of which were presented earlier in chapter 2.4. Recently, several articles, editorials and letters to the editor have been published discussing the value of screening tests (Bahr, 2016a, 2016b; Clarsen & Berge, 2016; Cook, 2016; McCunn et al., 2016; McCunn & Meyer, 2016). A number of experts in the field of sports medicine were asked about their views on the future research priorities in terms of

attempts to reduce the rates of injury and illness in sports. In the report, it was predicted that over the next 10 years,

“We will have realized that attempting to predict injury risk from pre-participation screening tests is futile.” (Finch et al., 2017)

If we accept this and discard the goal of predicting injury risk using specific tests, it does not mean that we must discard the valid and reliable tests that are in fact associated with injury risk, as these tests can be used to measure the development of neuromuscular control (Herrington et al., 2015; Noyes, Barber-Westin, Fleskenstein, Walsh, & West, 2005). Preliminary results suggest that the SLS can be used to measure improvement in frontal plane knee control after neuromuscular training (Herrington et al., 2015). The authors compared two programs, strength training and jump-landing, to examine their effects on the FPKPA. The strength training program produced significant improvements in the FPKPA among healthy female participants compared to both the jump-landing program group and the control group. However, future studies on this topic are needed. In addition, the possibility of using the FPKPA during the SLS in return-to-play assessments should be explored.

It is important to differentiate between a risk factor and the predictive value of a test. Due to the multifactorial nature of sports injuries, attempts to predict who will become injured do not seem feasible. Moreover, if such a test existed, would it cause harm? Would it cause athletes to give up their sport due to fear of injury? Despite the lack of predictive value, identifying and correcting movement control deficits, as well as other risk factors, is important. The results of this doctoral thesis further support the previous findings that movement control deficits can increase the risk of lower extremity injuries and should be directly addressed with training.

6.5 Age, sex, and side-to-side differences in frontal plane knee control

In Studies III and IV, age, sex, and side-to-side differences in frontal plane knee control were investigated.

6.5.1 Leg dominance

Leg dominance can be defined as an imbalance of muscular strength, flexibility, and/or joint kinematics between the lower extremities (Myer et al., 2004). Overly relying on the stronger leg is considered to place the dominant leg under greater stress, whereas the weaker, non-dominant leg becomes unable to effectively absorb even the average forces generated during athletic tasks (Ford et al., 2003). A difference of over 15% is considered to predispose the athlete to injuries (Hewitt, Cronin, & Hume, 2012). In collegiate athletes, elevated injury risk was detected in athletes with asymmetries in strength and flexibility (Knapik et al., 1991). Injury risk increased when the isokinetic right knee flexion strength or the passive right hip extension ROM was 15% greater compared to the left side. The authors hypothesised that the greater force generated by the right leg could result in damage to the left leg knee flexors if the muscles are not able to adequately absorb or transfer the force. In high school and collegiate athletes, asymmetry between the right and left leg reach distance during the star excursion balance test (SEBT) has been associated with a higher risk of injury (Plisky et al., 2006; C. A. Smith et al., 2015). In male youth football players, peak landing force asymmetry in the single-leg countermovement jump was associated with a higher risk of injuries (Read et al., 2018). The IPEPs can be useful in reducing the side-to-side differences between lower extremities. Utilising an IPEP has been shown to generate more significant improvement in the strength of the non-dominant leg compared to the dominant leg, thereby correcting leg dominance (Hewett, Stroupe, Nance, & Noyes, 1996).

It has been previously reported that leg dominance is prevalent in male youth football players (Atkins, Bentley, Hurst, Sinclair, & Hesketh, 2013; Daneshjoo, Rahnema, Mokhtar, & Yusof, 2013). The results of Study IV are in agreement with the previous findings on boys, and significant side-to-side differences were also detected in girls in the present study. One interesting finding is that the side-to-side differences in the FPKPA between the dominant and non-dominant leg were detected in the youngest girls (U11) and the oldest boys (U13 and U14). This could indicate that side-to-side asymmetry increases during pubertal growth. It has been previously reported that adolescent girls demonstrate poorer knee control during compared to before pubertal growth (Ford, Shapiro, Myer, Van Den Bogert, & Hewett, 2010). However, this cannot be validated using our data since no maturity estimates suitable for both sexes were utilised. However, our results further support the finding of Atkins and colleagues (2013) that side-to-side imbalances

considerably increase during the age that typically aligns with a period of rapid growth. Prepubescent athletes possess great potential to develop optimal biomechanical movement patterns and decrease the risk of injury by regular neuromuscular training (Hewett et al., 2016). Therefore, it is important to implement injury prevention protocols as part of regular training in childhood and early adolescence, prior to the start of the pubertal growth spurt (Myer, Faigenbaum, et al., 2011; Rumpf & Cronin, 2012).

6.5.2 Age and sex

Among the young football players, the mean FPKPA decreased with age, indicating age-related improvements. In the older cohort of basketball and floorball players, age-related differences were only prevalent in males, with older males displaying better knee control compared to the younger. It has been previously reported that frontal plane knee control in landings declines with age in female but not in male athletes (Sasaki et al., 2013). In Study III, significant sex differences in the FPKPA were detected among the older players. This is in agreement with a previous meta-analysis concluding that in adolescent athletes, sex differences in knee control increase with age (Holden et al., 2016). It has been suggested that boys can regain and improve their neuromuscular control after the adolescent growth spurt, but that this regain is not observed in girls (Hewett, Myer, & Ford, 2004). It has been reported that after the cessation of pubertal growth, female athletes do not make great gains in strength levels (Beunen & Malina, 1988), which may be related to the reduced knee control seen in females. These results indicate that including regular knee control exercises in training programs is critical for adolescent female athletes.

The mean FPKPA did not differ between males and females in young football players or in the cohort of basketball and floorball players. When comparing the older basketball and football players (>15.7 years), males displayed significantly better knee control on the left and the non-dominant leg compared to females. In a previous study utilising visual assessment of frontal plane knee control during the SLS test, no differences were detected between sexes. However, sex differences in frontal plane knee control have been reported in landing kinematics. A meta-analysis investigating landing biomechanics in adolescent athletes reported that females demonstrate significantly greater knee valgus compared to males (Holden et al., 2016). It is possible that the ground reaction forces during landing contribute

to the sex differences in knee control: compared to males, females may be unable to absorb the force as well. The fact that the SLS is a slower movement without impact might explain the low prevalence of sex differences in the FPKPA during the SLS in adolescent athletes.

6.6 Strengths and limitations

The main purpose of this doctoral dissertation was to address a knowledge gap regarding the predictive value of the single-leg squat (SLS) test. Several observational studies describing different aspects of the SLS have been previously published. While some of these studies have indicated that the SLS has the potential to be developed in to a screening tool, this topic had not been directly investigated. Addressing this knowledge gap is considered a major strength of this doctoral dissertation.

The part of this doctoral dissertation involving an examination of the role of the frontal plane as a lower extremity risk factor is based on two large prospective studies. These prospective studies, with their large cohorts and low drop-out rates, represent another strength of this work.

Previous studies have explored the validity and within-day and between-days reliability of the 2D FPKPA, and it has been reported to be a valid and reliable tool to measure frontal plane knee motions (McLean et al., 2005; Munro et al., 2012). The use of a single person, who was blinded to the future injury status, to perform all the 2D video analysis used in this dissertation is a strength since it can be considered valuable for the reliability of the measurements. However, since the inter-tester reliability of the 2D video analysis has not been determined, it is difficult to predict if similar results would be reproduced by another person, which limits the generalisability of the results. In addition, there are potential sources of measurement bias in the 2D video analysis. Some athletes performed the SLS with a significant trunk forward lean, limiting the visibility of the ASIS markers in some cases. In these cases, the last point at which the markers were visible was determined, and the marker movement was assessed based on the movement of the pelvis. This is a limitation of the 2D video analysis method. Another potential source of measurement bias occurred due to always performing the SLS test on the right leg first, which could have been eliminated by randomising the starting leg.

The results of this thesis provide important practical value to physiotherapists, athletic trainers, and physicians working with young athletes, as well as to coaches,

athletes, and parents. Based on this work, we know that the single-leg squat can be a useful tool to identify movement control deficits. We also have more evidence that improving frontal plane knee control is important for young athletes. These practical implications are considered definitive strengths of this work.

However, there are some additional limitations. In Study I, the use of a non-validated questionnaire is a limitation. In addition, the retrospective method may have introduced a recall bias. While the large nationally representative sample is a strength, the low response rate is a potential cause of selection bias. For these reasons, the results of Study I should be interpreted with caution.

In Study IV, the SLS procedure was too demanding for some of the participants. This was somewhat surprising since the test procedure was piloted on a team of young floorball players and no issues with the test procedure were recorded. Subjects who were unable to perform an adequate number of SLS on either leg had to be excluded from the risk factor analysis, which most likely affected the results. It is unfortunate that these subjects could not be analysed because they had trouble with knee control, and it should be considered a source of bias.

The possibility of type II error in Studies III and IV must be considered. Statistical power calculations were performed for the PROFITS study and the Sports Injury Prevention in Youth Football study. However, in Study III only the players with no self-reported injury during the 12 months prior to the study were included in the analysis; in Study IV, only the control group of the cluster-randomised controlled trial was included. These limitations to the included subjects may have weakened the statistical power.

The injury registration methods are a potential source of bias. In Study III, a coaching staff-based registration was employed. It is possible that the coaching staff was not aware of minor injuries, which may have limited the validity of the results. In addition to the registration method, injury definitions are another potential source of bias. In the self-administered questionnaire in Study I, no definition of injury was given. In Study III, only time-loss injuries were recorded, whereas in Study IV, slight injuries that did not result in missed training or match play were also recorded.

Attempts were made to control for the potentially confounding factors. In Studies III and IV, before the risk factor analysis, the mean values of the basic characteristics of the injured and uninjured players were compared to identify potential confounding factors. The potentially confounding effects of the team were controlled for in the risk factor analysis by incorporating them as random

effects. In Study I, age- and sex-adjusted analyses were used. However, it is still possible that certain confounders were not identified.

6.7 Future implications

Going forward, an interesting future study would be to replicate Study III in another cohort of young team sport athletes to investigate if the same associations between the FPKPA and lower extremity injuries could be detected.

In the future, it is important to use validated tools to continuously monitor the incidence of adolescent PA-related injuries in Finland. Currently the information is limited to retrospective studies is mostly self-reported. Surveillance methods need to be established to monitor the trend of PA-related injuries and its population burden.

As more and more injury risk factors are identified, the interaction between the risk factors can be explored further. In the future, it would be interesting to study the interaction between frontal plane knee control and training loads, anatomical characteristics, range of motion and strength measurements. This may reveal clusters of factors that together increase the risk of injury, as has been done in the context of handball (Møller et al., 2017).

Further research might also explore if the 2D analysis of the SLS is a suitable tool to measure improvements in knee control after training, as some previous studies have suggested. With advancements in technology, such as movement analysis tools for smart phones, calculating the FPKPA could be done quickly in a field setting. For an athlete, quantitative feedback on knee control could be a valuable motivational tool.

To take this even further and to collect more data than just the FPKPA, the use of wearable sensors in knee control research would be an interesting future step. Wearable sensors carry the potential to measure knee control in real-time sporting events, such as games and practice. This could represent a very valuable contribution to sports injury research. It is conceivable that the use of wearable sensors might enable data sets similar to those currently collected in 3D laboratories to be collected in the field setting.

7 CONCLUSIONS

The conclusions of the present thesis are the following:

- 1) The prevalence of adolescent physical activity injuries is highest in sports club activities. More preventative measures are needed to reduce the injury burden.
- 2) The visual assessment of frontal plane knee control on a 3-point graded scale correlates relatively well with the frontal plane knee projection angle measured by 2D video analysis. For clinical practice, the visual assessment may be a suitable tool for crude knee control assessment when performed by experienced observers.
- 3) Among older adolescents, a large frontal plane knee projection angle during the single-leg squat is associated with higher odds of acute lower extremity injuries.
- 4) 2D analysis of the single-leg squat test is not predictive of future injuries in young team sport athletes.
- 5) Young football players display significant side-to-side differences in frontal plane knee control between the dominant and non-dominant leg. The side-to-side differences are significant among boys and girls. Sex-related differences were present among older adolescents, with males displaying superior knee control.
- 6) Side-to-side difference in frontal plane knee control but is not associated with lower extremity injuries among young football players.

ACKNOWLEDGEMENTS

This study was carried out at the Tampere Research Center of Sports Medicine and the UKK Institute for Health Promotion Research, Tampere, Finland. The PROFITS study and the Sports Injury Prevention in Youth Football study were financially supported by the Ministry of Education and the Competitive State Research Financing of the Expert Responsibility Area of Tampere University Hospital. The data collection of AHLS was financed by the Ministry of Social Affairs and Health. This doctoral dissertation was also financially supported by the Foundation of Sports Institute (Urheiluopistosäätiö), the Scientific Council of City of Tampere (Tampereen kaupungin tiederahasto), and the Eerikkilä Sports Institute, which are gratefully acknowledged.

I would like to thank my supervisors Docent Jari Parkkari and Professor Arja Rimpelä. Docent Jari Parkkari, you have been a great source of support throughout my doctoral studies. During these years of working together you have been able to pass on some of your vast knowledge on sports injury research to me but even more importantly, I hope I have been able to absorb even a small portion of your positive attitude. Professor Arja Rimpelä, I am extremely thankful for having the opportunity to work with you and be part of your NEDIS seminar group. Your knowledge on adolescent health research is amazing and I have learned so much from you.

Assistant professor Kati Pasanen, this doctoral thesis would not exist without you. From that day over a decade ago when you recruited me to be a part-time research assistant in the floorball study, your role in my research career has been paramount. From the bottom of my heart, I thank you for your mentorship and friendship.

I had the honour of having Professor Carolyn Emery and Docent Timo Järvelä perform their external reviews of this doctoral dissertation. I thank you for your thorough work and excellent comments which improved the quality of this work.

Professor Reed Ferber, thank you for honouring my work by agreeing to be my opponent in my public defense.

To my co-authors Doctor Pekka Kannus, Doctor Tron Krosshaug, Doctor Tommi Vasankari, Doctor Janne Avela, Doctor Urho Kujala, Doctor Ari

Heinonen, Doctor Kathrin Steffen, Doctor Hannele Forsman, Doctor Jarmo Perttunen, B.M. Lotta Karhola, and B.M. Hillevi Arkkila, thank you for your contributions. Statistician Kari Tokola, I am grateful for your statistical advice.

Irja ja Mari, you have been an essential part of this process and it is impossible to put to words how important your friendship has been. The best memories from this time won't be the accepted articles; the experiences shared with the two of you will always take the highest spot on the podium.

To all my colleagues at Tampere Research Center of Sports Medicine and the UKK Institute, thank you. I am thankful for the support and the guidance I have received, but also for all the laughs we have shared. All the research assistants who worked in the PROFITS study and the Sports Injury Prevention in Youth Football study, I am grateful for your contribution.

Kyösti Lampinen, I thank you for your commitment to research and injury prevention, your engagement made our football study possible. I also want to thank Hannele Forsman and the entire staff of Eerikkilä Sports Institute Training Center for your commitment in the research and implementation stages. It has been a pleasure and privilege to work with you.

Tommi Vasankari, Jari Parkkari, and Kyösti Lampinen, I thank you for your great contributions for securing financing for my work.

To all my friends, thank you for your support. Thank you for allowing me to share my triumphs, as well as the trials and tribulations with you. And thank you for all the fun times we have shared.

Finally, I owe my deepest gratitude to my loving family. My mother Ulla and my father Pauli, thank you for your boundless love and support and for teaching me the importance of setting goals and working hard to reach them. My brother Teemu, my brother Riku, my sister-in-law Leena, thank you all for always having an interest in my work and providing love and support. My delightful nephew and godson Frans and lovely niece Fiona, thank you for the opportunities to play and laugh with you.

Tampere, April 11th, 2018

Anu Räisänen

REFERENCES

- Ageberg, E., Bennell, K. L., Hunt, M. A., Simic, M., Roos, E. M., & Creaby, M. W. (2010). Validity and inter-rater reliability of medio-lateral knee motion observed during a single-limb mini squat. *BMC Musculoskeletal Disorders*, *11*, 265.
- Agel, J., Arendt, E. A., & Bershadsky, B. (2005). Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: A 13-year review. *American Journal of Sports Medicine*, *33*(4), 524–31. <http://doi.org/10.1177/0363546504269937>
- Agel, J., Olson, D. E., Dick, R., Arendt, E. A., Marshall, S. W., & Sikka, R. S. (2007). Descriptive epidemiology of collegiate women's basketball injuries: National Collegiate Athletic Association injury surveillance system, 1988-1989 through 2003-2004. *Journal of Athletic Training*, *42*(2), 202–10.
- Agresta, C. E., Church, C., Henley, J., Duer, T., & O'Brien, K. (2016). Single leg squat performance in active adolescents age 8 to 17 years. *Journal of Strength and Conditioning Research*, *31*(5), 1187–91. <http://doi.org/10.1519/JSC.0000000000001617>
- Altman, D. G. (1991). *Practical statistics for medical research*. London, UK: Chapman and Hall.
- Arendt, E. A., & Dick, R. (1995). Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *American Journal of Sports Medicine*, *23*(6), 694–701.
- Asker, M., Brooke, H. L., Waldén, M., Tranaeus, U., Johansson, F., Skillgate, E., & Holm, L. W. (2018). Risk factors for, and prevention of, shoulder injuries in overhead sports: a systematic review with best- evidence synthesis. *British Journal of Sports Medicine*, March 26 [Epub ahead of print]. <http://doi.org/10.1136/>
- Atkins, S., Bentley, I., Hurst, H., Sinclair, J., & Hesketh, C. (2013). The presence of bilateral imbalance of the lower limbs in elite youth soccer players of different ages. *Journal of Strength and Conditioning Research*, *30*(4), 1007–13. <http://doi.org/10.1519/JSC.0b013e3182987044>
- Bahr, R. (2016a). Why screening tests to predict injury do not work-and probably never will...: a critical review. *British Journal of Sports Medicine*, *50*(13), 776–80. <http://doi.org/10.1136/bjsports-2016-096256>
- Bahr, R. (2016b). Response to “Screening for risk factors: if you liked it then you should have put a number on it.” *British Journal of Sports Medicine*,

- 50(21), 1354. <http://doi.org/http://dx.doi.org/10.1136/bjsports-2016-096465>
- Bahr, R., & Holme, I. (2003). Risk factors for sports injuries—a methodological approach. *British Journal of Sports Medicine*, 37(5), 384–92. <http://doi.org/10.1136/bjsm.37.5.384>
- Baldon, R. D. M., Lobato, D. F. M., Carvalho, L. P., Santiago, P. R. P., Benze, B. G., & Serrão, F. V. (2011). Relationship between eccentric hip torque and lower-limb kinematics: Gender differences. *Journal of Applied Biomechanics*, 27(3), 223–32. <http://doi.org/10.1123/jab.27.3.223>
- Bangsbo, J., Krstrup, P., Duda, J., Hillman, C., Andersen, L. B., Weiss, M., ... Elbe, A.-M. (2016). The Copenhagen Consensus Conference 2016: children, youth, and physical activity in schools and during leisure time. *British Journal of Sports Medicine*, 50(19), 1177–8. <http://doi.org/10.1136/bjsports-2016-096325>
- Bardenett, S. M., Micca, J. J., DeNoyelles, J. T., Miller, S. D., Jenk, D. T., & Brooks, G. S. (2015). Functional Movement Screen normative values and validity in high school athletes: can the FMS™ be used as a predictor of injury? *International Journal of Sports Physical Therapy*, 10(3), 303–8.
- Bell, D. R., Post, E. G., Trigsted, S. M., Hetzel, S., McGuine, T. A., & Brooks, M. A. (2016). Prevalence of sport specialization in high school athletics: A 1-year observational study. *The American Journal of Sports Medicine*, 44(6), 1469–74. <http://doi.org/10.1177/0363546516629943>
- Beunen, G. P., & Malina, R. M. (1988). Growth and physical performance relative to the timing of the adolescent spurt. *Exercise and Sport Science Reviews*, 16(1), 503–40. <http://doi.org/10.1249/00003677-198800160-00018>
- Beynnon, B. D., Vacek, P. M., Murphy, D., Alosa, D., & Paller, D. (2005). First-time inversion ankle ligament trauma. The effects of sex, level of competition, and sport on the incidence of injury. *The American Journal of Sports Medicine*, 33(10), 1485–91. <http://doi.org/10.1177/0363546505275490>
- Bijur, P., Trumble, A., Harel, Y., Overpeck, M. D., Jones, D., & Scheidt, P. C. (1995). Sports and recreation injuries in US children and adolescents. *Archives of Pediatrics & Adolescent Medicine*, 149(9), 1009–16.
- Bittencourt, N., Ocarino, J. M., Mendonça, L. D. M., Hewett, T. E., & Fonseca, S. T. (2012). Foot and hip contributions to high frontal plane knee projection angle in athletes: a classification and regression tree approach. *Journal of Orthopaedic & Sports Physical Therapy*, 42(12), 996–1005. <http://doi.org/10.2519/jospt.2012.4041>
- Black, A. M., Hagel, B. E., Palacios-Derflingher, L., Schneider, K. J., & Emery, C. A. (2017). The risk of injury associated with body checking among Pee Wee ice hockey players: an evaluation of Hockey Canada’s national body

- checking policy change. *British Journal of Sports Medicine*, 51(24), 1767–72.
<http://doi.org/10.1136/>
- Black, A. M., Macpherson, A. K., Hagel, B. E., Romiti, M. A., Palacios-Derflingher, L., Kang, J., ... Emery, C. A. (2016). Policy change eliminating body checking in non-elite ice hockey leads to a threefold reduction in injury and concussion risk in 11- and 12-year-old players. *British Journal of Sports Medicine*, 50(1), 55–61.
<http://doi.org/10.1136/bjsports-2015-095103>
- Bloemers, F., Collard, D. C. M., Chin A Paw, M., Van Mechelen, W., Twisk, J., & Verhagen, E. (2012). Physical inactivity is a risk factor for physical activity-related injuries in children. *British Journal of Sports Medicine*, 46(9), 669–74. <http://doi.org/10.1136/bjsports-2011-090546>
- Bonazza, N. A., Smuin, D., Onks, C. A., Silvis, M. L., & Dhawan, A. (2017). Reliability, validity, and injury predictive value of the Functional Movement Screen. A systematic review and meta-analysis. *The American Journal of Sports Medicine*, 45(3), 725–32.
<http://doi.org/10.1177/0363546516641937>
- Boudreau, S. N., Dwyer, M. K., Mattacola, C. G., Lattermann, C., Uhl, T. L., & Mckeon, J. M. (2009). Hip-muscle activation during the lunge, single-leg squat, and step-up-and-over exercises. *Journal of Sport Rehabilitation*, 18(1), 91–103.
- Bowen, L., Gross, A. S., Gimpel, M., & Li, F. X. (2017). Accumulated workloads and the acute:chronic workload ratio relate to injury risk in elite youth football players. *British Journal of Sports Medicine*, 51(5), 452–9.
<http://doi.org/10.1136/bjsports-2015-095820>
- Brink, M. S., Visscher, C., Arends, S., Zwerver, J., Post, W. J., & Lemmink, K. A. (2010). Monitoring stress and recovery: new insights for the prevention of injuries and illnesses in elite youth soccer players. *British Journal of Sports Medicine*, 44(11), 809–15. <http://doi.org/10.1136/bjsm.2009.069476>
- Burt, C. W., & Overpeck, M. D. (2001). Emergency visits for sports-related injuries. *Annals of Emergency Medicine*, 37(3), 301–8.
- Butler, R. J., Lehr, M. E., Fink, M. L., Kiesel, K. B., & Plisky, P. J. (2013). Dynamic balance performance and noncontact lower extremity injury in college football players: an initial study. *Sports Health*, 5(5), 417–22.
<http://doi.org/10.1177/1941738113498703>
- Caine, D., Maffulli, N., & Caine, C. (2008). Epidemiology of injury in child and adolescent sports: injury rates, risk factors, and prevention. *Clinics in Sports Medicine*, 27(1), 19–50. <http://doi.org/10.1016/j.csm.2007.10.008>
- Carter, C. W., & Micheli, L. J. (2011). Training the child athlete: physical fitness, health and injury. *British Journal of Sports Medicine*, 45(11), 880–5.
<http://doi.org/10.1136/bjsports-2011-090201>
- Chalmers, S., Debenedictis, T. A., Zacharia, A., Townsley, S., Gleeson, C.,

- Lynagh, M., ... Fuller, J. T. (2018). Asymmetry during Functional Movement Screening and injury risk in junior football players: A replication study. *Scandinavian Journal of Medicine & Science in Sports*, 28(3), 1281–7. <http://doi.org/10.1111/sms.13021>
- Chalmers, S., Fuller, J. T., DeBenedictis, T. A., Townsley, S., Lynagh, M., Gleeson, C., ... Magarey, M. (2017). Asymmetry during preseason Functional Movement Screen testing is associated with injury during a junior Australian football season. *Journal of Science and Medicine in Sport*, 20(7), 653–7. <http://doi.org/10.1016/j.jsams.2016.12.076>
- Chappell, J. D., & Limpisvasti, O. (2008). Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *The American Journal of Sports Medicine*, 36(6), 1081–6. <http://doi.org/10.1177/0363546508314425>
- Chmielewski, T. L., Hodges, M. J., Horodyski, M., Bishop, M. D., Conrad, B. P., & Tillman, S. M. (2007). Investigation of clinician agreement in evaluating movement quality during unilateral lower extremity functional tasks: a comparison of 2 rating methods. *Journal of Orthopaedic & Sports Physical Therapy*, 37(3), 122–9.
- Chorba, R., Chorba, D., Bouillon, L., Overmyer, C., & Landis, J. (2010). Use of a functional movement screening tool to determine injury risk in female collegiate athletes. *North American Journal of Sports Physical Therapy*, 5(2), 47–54.
- Claiborne, T. L., Armstrong, C. W., Gandhi, V., & Pincivero, D. M. (2006). Relationship between hip and knee strength and knee valgus during a single leg squat. *Journal of Applied Biomechanics*, 22(1), 41–50.
- Clarsen, B., & Berge, H. M. (2016). Screening is dead. Long live screening! *British Journal of Sports Medicine*, 50(13), 769. <http://doi.org/10.1136/bjsports-2016-096475>
- Clarsen, B., Rønsen, O., Myklebust, G., Flørenes, T. W., & Bahr, R. (2014). The Oslo Sports Trauma Research Center questionnaire on health problems: A new approach to prospective monitoring of illness and injury in elite athletes. *British Journal of Sports Medicine*, 48(9), 754–60. <http://doi.org/10.1136/bjsports-2012-092087>
- Clausen, M., Zebis, M. K., Møller, M., Krstrup, P., Hölmich, P., Wedderkopp, N., ... Thorborg, K. (2014). High injury incidence in adolescent female soccer. *American Journal of Sports Medicine*, 42(10), 2487–94. <http://doi.org/10.1177/0363546514541224>
- Cole, T. J., Bellizzi, M. C., Flegal, K. M., & Dietz, W. H. (2000). Establishing a standard definition for child overweight and obesity worldwide: international survey. *BMJ*, 320(7244), 1240. <http://doi.org/10.1136/bmj.320.7244.1240>
- Cole, T. J., Flegal, K. M., Nicholls, D., & Jackson, A. (2007). Body mass index

- cut offs to define thinness in children and adolescents. *BMJ*, 335(7612), 194.
- Collard, D. C. M., Verhagen, E., Chin A Paw, M. J. M., & van Mechelen, W. (2008). Acute physical activity and sports injuries in children. *Applied Physiology, Nutrition, and Metabolism*, 33(2), 393–401. <http://doi.org/10.1139/H07-182>
- Collard, D. C. M., Verhagen, E., van Mechelen, W., Heymans, M. W., & Chinapaw, M. J. M. (2011). Economic burden of physical activity-related injuries in Dutch children aged 10-12. *British Journal of Sports Medicine*, 45(13), 1058–63. <http://doi.org/10.1136/bjsm.2010.082545>
- Conn, J. M., Annest, J. L., & Gilchrist, J. (2003). Sports and recreation related injury episodes in the US population, 1997-99. *Injury Prevention*, 9(2), 117–23.
- Cook, C. (2016). Predicting future physical injury in sports: it's a complicated dynamic system. *British Journal of Sports Medicine*, 50(22), 1356–57. <http://doi.org/10.1136/bjsports-2015-095796>
- Crossley, K. M., Zhang, W.-J., Schache, A., Bryant, A., & Cowan, S. M. (2011). Performance on the single-leg squat task indicates hip abductor muscle function. *American Journal of Sports Medicine*, 39(4), 866–73. <http://doi.org/10.1177/0363546510395456>
- Dallinga, J. M., Benjaminse, A., & Lemmink, K. A. P. M. (2012). Which screening tools can predict injury of the lower extremities in team sports? *Sports Medicine*, 42(9), 791–815.
- Daneshjoo, A., Rahnama, N., Mokhtar, A. H., & Yusof, A. (2013). Bilateral and unilateral asymmetries of isokinetic strength and flexibility in male young professional soccer players. *Journal of Human Kinetics*, 36(1), 45–53. <http://doi.org/10.2478/hukin-2013-0005>
- De Blaiser, C., Roosen, P., Willems, T., Danneels, L., Bossche, L. V., & De Ridder, R. (2018). Is core stability a risk factor for lower extremity injuries in an athletic population? A systematic review. *Physical Therapy in Sport*, 30(3), 48–56. <http://doi.org/10.1016/j.ptsp.2017.08.076>
- de Loës, M., Dahlstedt, L. J., & Thomée, R. (2000). A 7-year study on risks and costs of knee injuries in male and female youth participants in 12 sports. *Scandinavian Journal of Medicine & Science in Sports*, 10(2), 90–7. <http://doi.org/10.1034/j.1600-0838.2000.010002090.x>
- De Ridder, R., Witvrouw, E., Dolphens, M., Roosen, P., & Van Ginckel, A. (2016). Hip strength as an intrinsic risk factor for lateral ankle sprains in youth soccer players: A 3-season prospective study. *The American Journal of Sports Medicine*, 45(2), 410–6. <http://doi.org/10.1177/0363546516672650>
- Decloe, M. D., Meeuwisse, W. H., Hagel, B. E., & Emery, C. A. (2014). Injury rates, types, mechanisms and risk factors in female youth ice hockey. *British Journal of Sports Medicine*, 48(1), 51–6.

- <http://doi.org/10.1136/bjsports-2012-091653>
- Dekker, R., Kingma, J., Groothoff, J. W., Eisma, W. H., & Ten Duis, H. J. (2000). Measurement of severity of sports injuries: an epidemiological study. *Clinical Rehabilitation*, 14(6), 651–6.
- Devan, M. R., Pescatello, L. S., Faghri, P., & Anderson, J. (2004). A prospective study of overuse knee injuries among female athletes with muscle imbalances and structural abnormalities. *Journal of Athletic Training*, 39(3), 263–7.
- Dill, K. E., Begalle, R. L., Frank, B. S., Zinder, S. M., & Padua, D. A. (2014). Altered knee and ankle kinematics during squatting in those with limited weight-bearing-lunge ankle-dorsiflexion range of motion. *Journal of Athletic Training*, 49(6), 723–32. <http://doi.org/10.4085/1062-6050-49.3.29>
- DiMattia, M. A., Livengood, A. L., Uhl, T. L., Mattacola, C. G., & Malone, T. R. (2005). What are the validity of the single-leg-squat test and its relationship to hip-abduction strength? *Journal of Sport Rehabilitation*, 14(2), 108–23. <http://doi.org/10.1123/jsr.14.2.108>
- Distefano, L. J., Padua, D. A., Blackburn, J. T., Garrett, W. E., Guskiewicz, K. M., & Marshall, S. W. (2010). Integrated injury prevention program improves balance and vertical jump height in children. *Journal of Strength and Conditioning Research*, 24(2), 332–42.
- Dossa, K., Cashman, G., Howitt, S., West, B., & Murray, N. (2014). Can injury in major junior hockey players be predicted by a pre-season functional movement screen - a prospective cohort study. *The Journal of the Canadian Chiropractic Association*, 58(4), 421–7.
- Drew, M. K., & Finch, C. F. (2016). The relationship between training load and injury, illness and soreness: a systematic and literature review. *Sports Medicine*, 46(6), 861–83. <http://doi.org/10.1007/s40279-015-0459-8>
- Dwyer, M. K., Boudreau, S. N., Mattacola, C. G., Uhl, T. L., & Lattemann, C. (2010). Comparison of lower extremity kinematics and hip muscle activation during rehabilitation tasks between sexes. *Journal of Athletic Training*, 45(2), 181–90.
- Embree, T. E., Romanow, N. T. R., Djerboua, M. S., Morgunov, N. J., Bourdeaux, J. J., & Hagel, B. E. (2016). Risk factors for bicycling injuries in children and adolescents: A systematic review. *Pediatrics*, 138(5), e20160282. <http://doi.org/10.1542/peds.2016-0282>
- Emery, C. A. (2003). Risk factors for injury in child and adolescent sport: a systematic review of the literature. *Clinical Journal of Sport Medicine*, 13(4), 256–68. <http://doi.org/10.1097/00042752-200307000-00011>
- Emery, C. A. (2005). Injury prevention and future research. In N. Maffulli & D. Caine (Eds.), *Epidemiology of Pediatric Sports Injuries: Team Sports. Medicine and Sport Science*. (Vol. 49, pp. 170–91). Basel: Karger.
- Emery, C. A., & Meeuwisse, W. H. (2006). Injury rates, risk factors, and

- mechanisms of injury in minor hockey. *The American Journal of Sports Medicine*, 34(12), 1960–9. <http://doi.org/10.1177/0363546506290061>
- Emery, C. A., Meeuwisse, W. H., & Hartmann, S. E. (2005). Evaluation of risk factors for injury in adolescent soccer: implementation and validation of an injury surveillance system. *The American Journal of Sports Medicine*, 33(12), 1882–91. <http://doi.org/10.1177/0363546505279576>
- Emery, C. A., Roy, T.-O., Whittaker, J. L., Nettel-Aguirre, A., & van Mechelen, W. (2015). Neuromuscular training injury prevention strategies in youth sport: a systematic review and meta-analysis. *British Journal of Sports Medicine*, 49(13), 865–70. <http://doi.org/10.1136/bjsports-2015-094639>
- Faude, O., Rößler, R., & Junge, A. (2013). Football injuries in children and adolescent players: are there clues for prevention? *Sports Medicine*, 43(9), 819–37.
- Ferber, R., Davis, I. M. C., & Williams, D. S. (2003). Gender differences in lower extremity mechanics during running. *Clinical Biomechanics*, 18(4), 350–7. [http://doi.org/10.1016/S0268-0033\(03\)00025-1](http://doi.org/10.1016/S0268-0033(03)00025-1)
- Ferber, R., Noehren, B., Hamill, J., & Davis, I. (2010). Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics. *Journal of Orthopaedic & Sports Physical Therapy*, 40(2), 52–8. <http://doi.org/10.2519/jospt.2010.3028>
- Finch, C. F. (2006). A new framework for research leading to sports injury prevention. *Journal of Science and Medicine in Sport*, 9(1-2), 3–9. <http://doi.org/10.1016/j.jsams.2006.02.009>
- Finch, C. F. (2012). Getting sports injury prevention on to public health agendas - addressing the shortfalls in current information sources. *British Journal of Sports Medicine*, 46(1), 70–4.
- Finch, C. F., Bahr, R., Drezner, J. A., Dvorak, J., Engebretsen, L., Hewett, T. E., ... Verhagen, E. (2017). Towards the reduction of injury and illness in athletes: defining our research priorities. *British Journal of Sports Medicine*, 51(16), 1178–82. <http://doi.org/10.1136/bjsports-2016-097042>
- Finch, C. F., & Cassell, E. (2006). The public health impact of injury during sport and active recreation. *Journal of Sports Sciences*, 24(6), 490–7.
- Finch, C. F., Mitchell, R., & Boufous, S. (2011). Trends in hospitalised sport/leisure injuries in New South Wales, Australia - Implications for the targeting of population-focussed preventive sports medicine efforts. *Journal of Science and Medicine in Sport*, 14(1), 15–21. <http://doi.org/10.1016/j.jsams.2010.03.009>
- Finch, C. F., & Owen, N. (2001). Injury prevention and the promotion of physical activity: what is the nexus? *Journal of Science and Medicine in Sport*, 4(1), 77–87.
- Finch, C. F., Wong Shee, A., & Clapperton, A. (2014). Time to add a new priority target for child injury prevention? The case for an excess burden

- associated with sport and exercise injury: population-based study. *BMJ Open*, 4(7), e005043. <http://doi.org/10.1136/bmjopen-2014-005043>
- Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Medicine & Science in Sports & Exercise*, 35(10), 1745–50.
- Ford, K. R., Shapiro, R., Myer, G. D., Van Den Bogert, A. J., & Hewett, T. E. (2010). Longitudinal sex differences during landing in knee abduction in young athletes. *Medicine & Science in Sports & Exercise*, 42(10), 1923–31. <http://doi.org/10.1249/MSS.0b013e3181dc99b1>
- Fort-Vanmeerhaeghe, A., Romero-Rodriguez, D., Montalvo, A., Kiefer, A., Lloyd, R. S., & Myer, G. D. (2016). Integrative neuromuscular training and injury prevention in youth athletes. Part I: Identifying risk factors. *Strength and Conditioning Journal*, 38(3), 36–48.
- Fox, A. S., Bonacci, J., McLean, S. G., Spittle, M., & Saunders, N. (2016). A systematic evaluation of field-based screening methods for the assessment of anterior cruciate ligament (ACL) injury risk. *Sports Medicine*, 46(5), 715–35. <http://doi.org/10.1007/s40279-015-0443-3>
- Froholdt, A., Olsen, O. E., & Bahr, R. (2009). Low risk of injuries among children playing organized soccer. A prospective cohort study. *The American Journal of Sports Medicine*, 37(6), 1155–60. <http://doi.org/10.1177/0363546508330132>
- Fuller, C. W., Ekstrand, J., Junge, A., Andersen, T. E., Bahr, R., Dvorak, J., ... Meeuwisse, W. H. (2006). Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *British Journal of Sports Medicine*, 40(3), 193–201. <http://doi.org/10.1136/bjsm.2005.025270>
- Gabbett, T. J. (2005). Physiological and anthropometric characteristics of junior rugby league players over a competitive season. *Journal of Strength and Conditioning Research*, 19(4), 764–71.
- Gabbett, T. J. (2016). The training-injury prevention paradox: Should athletes be training smarter and harder? *British Journal of Sports Medicine*, 50(5), 273–80. <http://doi.org/10.1136/bjsports-2015-095788>
- Garrison, M., Westrick, R., Johnson, M. R., & Benenson, J. (2015). Association between the Functional Movement Screen and injury development in college athletes. *International Journal of Sports Physical Therapy*, 10(1), 21–8.
- Glover, T. A., & Albers, C. A. (2007). Considerations for evaluating universal screening assessments. *Journal of School Psychology*, 45(2), 117–135. <http://doi.org/10.1016/j.jsp.2006.05.005>
- Gomez, J., Ross, S., Calmbach, W., Kimmel, R., Schmidt, D., & Dhanda, R. (1998). Body fatness and increased injury rates in high school football linemen. *Clinical Journal of Sport Medicine*, 8(2), 115–20.
- Graci, V., & Salsich, G. B. (2015). Trunk and lower extremity segment

- kinematics and their relationship to pain following movement instruction during a single-leg squat in females with dynamic knee valgus and patellofemoral pain. *Journal of Science and Medicine in Sport*, 18(3), 343–347. <http://doi.org/10.1016/j.jsams.2014.04.011>
- Graci, V., Van Dillen, L. R., & Salsich, G. B. (2012). Gender differences in trunk, pelvis and lower limb kinematics during a single leg squat. *Gait and Posture*, 36(3), 461–6. <http://doi.org/10.1016/j.gaitpost.2012.04.006>
- Gribble, P. A., Hertel, J., & Plisky, P. (2012). Using the star excursion balance test to assess dynamic postural-control deficits and outcomes in lower extremity injury: A literature and systematic review. *Journal of Athletic Training*, 47(3), 339–57. <http://doi.org/10.4085/1062-6050-47.3.08>
- Gribble, P. A., Terada, M., Beard, M. Q., Kosik, K. B., Lepley, A. S., McCann, R. S., ... Thomas, A. C. (2015). Prediction of lateral ankle sprains in football players based on clinical tests and body mass index. *The American Journal of Sports Medicine*, 44(2), 460–7. <http://doi.org/10.1177/0363546515614585>
- Grimmer, K. A., Jones, D., & Williams, J. (2000). Prevalence of adolescent injury from recreational exercise: an Australian perspective. *Journal of Adolescent Health*, 27(4), 266–72. [http://doi.org/http://dx.doi.org/10.1016/S1054-139X\(00\)00120-8](http://doi.org/http://dx.doi.org/10.1016/S1054-139X(00)00120-8)
- Gunnoe, A. J., Horodyski, M., Tennant, K. L., & Murphey, M. (2001). The effect of life events on incidence of injury in high school football players. *Journal of Athletic Training*, 36(2), 150–5.
- Haapala, E. A., Väistö, J., Lintu, N., Westgate, K., Ekelund, U., Poikkeus, A. M., ... Lakka, T. A. (2017). Physical activity and sedentary time in relation to academic achievement in children. *Journal of Science and Medicine in Sport*, 20(6), 583–9. <http://doi.org/10.1016/j.jsams.2016.11.003>
- Hall, M. P., Paik, R. S., Ware, A. J., Mohr, K. J., & Limpisvasti, O. (2015). Neuromuscular evaluation with single-leg squat test at 6 months after anterior cruciate ligament reconstruction. *Orthopaedic Journal of Sports Medicine*, 3(3), 2325967115575900. <http://doi.org/10.1177/2325967115575900>
- Hamill, J., & Knutzen, K. M. (1995). *Biomechanical basis of human movement*. Philadelphia, PA: Lippincott Williams & Wilkins.
- Harris-Hayes, M., Steger-May, K., Koh, C., Royer, N. K., Graci, V., & Salsich, G. B. (2014). Classification of lower extremity movement patterns based on visual assessment: reliability and correlation with 2-dimensional video analysis. *Journal of Athletic Training*, 49(3), 304–10.
- Herrington, L. (2014). Knee valgus angle during single leg squat and landing in patellofemoral pain patients and controls. *Knee*, 21(2), 514–7.
- Herrington, L., Munro, A., & Comfort, P. (2015). A preliminary study into the effect of jumping-landing training and strength training on frontal plane

- projection angle. *Manual Therapy*, 20(5), 680–5.
<http://doi.org/10.1016/j.math.2015.04.009>
- Hertel, J., Braham, R. A., Hale, S. A., & Olmsted-kramer, L. (2006). Simplifying the Star Excursion Balance Test: Analyses of subjects with and without chronic ankle instability. *Journal of Orthopaedic & Sports Physical Therapy*, 36(3), 131–7.
- Hewett, T. E., Myer, G. D., & Ford, K. R. (2004). Decrease in neuromuscular control about the knee with maturation in female athletes. *The Journal of Bone and Joint Surgery*, 86(8), 1601–8. <http://doi.org/86/8/1601> [pii]
- Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S. J., Colosimo, A. J., McLean, S. G., ... Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *American Journal of Sports Medicine*, 33(4), 492–501.
<http://doi.org/10.1177/0363546504269591>
- Hewett, T. E., Myer, G. D., Ford, K. R., Paterno, M. V., & Quatman, C. E. (2016). Mechanisms, prediction, and prevention of ACL injuries: Cut risk with three sharpened and validated tools. *Journal of Orthopaedic Research*, 34(11), 1843–55. <http://doi.org/10.1002/jor.23414>
- Hewett, T. E., Paterno, M. V., & Myer, G. D. (2002). Strategies for enhancing proprioception and neuromuscular control of the knee. *Clinical Orthopaedics and Related Research*, (402), 76–94.
<http://doi.org/10.1097/01.blo.0000026962.51742.99>
- Hewett, T. E., Stroupe, A. L., Nance, T. A., & Noyes, F. R. (1996). Plyometric training in female athletes: Decreased impact forces and increased hamstring torques. *American Journal of Sports Medicine*, 24(6), 765–73.
- Hewitt, J., Cronin, J., & Hume, P. (2012). Multidirectional leg asymmetry assessment in sport. *Strength and Conditioning Journal*, 34(1), 82–6.
<http://doi.org/10.1519/SSC.0b013e31823e83db>
- Holden, S., Boreham, C., & Delahunt, E. (2016). Sex differences in landing biomechanics and postural stability during adolescence: A systematic review with meta-analyses. *Sports Medicine*, 46(2), 241–53.
<http://doi.org/10.1007/s40279-015-0416-6>
- Holden, S., Boreham, C., Doherty, C., & Delahunt, E. (2017). Two-dimensional knee valgus displacement as a predictor of patellofemoral pain in adolescent females. *Scandinavian Journal of Medicine & Science in Sports*, 27(2), 188–94. <http://doi.org/10.1111/sms.12633>
- Hollman, J. H., Galardi, C. M., Lin, I.-H., Voth, B. C., & Whitmarsh, C. L. (2014). Frontal and transverse plane hip kinematics and gluteus maximus recruitment correlate with frontal plane knee kinematics during single-leg squat test in women. *Clinical Biomechanics*, 29(4), 468–74.
- Hollman, J. H., Ginos, B. E., Kozuchowski, J., Vaughn, A. S., Krause, D. A., &

- Youdas, J. W. (2009). Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. *Journal of Sport Rehabilitation*, 18(1), 104–7.
- Horan, S. A., Watson, S. L., Carty, C. P., Sartori, M., & Weeks, B. K. (2014). Lower-limb kinematics of single-leg squat performance in young adults. *Physiotherapy Canada*, 66(3), 228–33. <http://doi.org/10.3138/ptc.2013-09>
- Hoshikawa, Y., Iida, T., Muramatsu, M., Ii, N., Nakajima, Y., Chumank, K., & Kanehisa, H. (2013). Effects of stabilization training on trunk muscularity and physical performances in youth soccer players. *Journal of Strength and Conditioning Research*, 27(11), 3142–9. <http://doi.org/10.1519/JSC.0b013e31828bed36>
- Hosmer, D. W., Lemeshow, S., & Sturdivant, R. (2013). *Applied logistic regression*. 3rd edition. (Electronic). John Wiley & Sons, Incorporated.
- Häggglund, M., & Waldén, M. (2015). Risk factors for acute knee injury in female youth football. *Knee Surgery, Sports Traumatology, Arthroscopy*, 24(3), 737–76. <http://doi.org/10.1007/s00167-015-3922-z>
- Inklaar, H., Bol, E., Schmikli, S. L., & Mosterd, W. L. (1996). Injuries in male soccer players: team risk analysis. *International Journal of Sports Medicine*, 17(3), 229–34.
- Jacobs, C. A., Uhl, T. L., Mattacola, C. G., Shapiro, R., & Rayens, W. S. (2007). Hip abductor function and lower extremity landing kinematics: Sex differences. *Journal of Athletic Training*, 42(1), 76–83.
- Janssen, I., & LeBlanc, A. G. (2010). Systematic review of the health benefits of physical activity and fitness in school-aged children and youth. *International Journal of Behavioral Nutrition and Physical Activity*, 7(5), 40. <http://doi.org/10.1186/1479-5868-7-40>
- Jayanthi, N. A., LaBella, C. R., Fischer, D., Pasulka, J., & Dugas, L. R. (2015). Sports-specialized intensive training and the risk of injury in young athletes: A clinical case-control study. *The American Journal of Sports Medicine*, 43(4), 794–801. <http://doi.org/10.1177/0363546514567298>
- Jespersen, E., Rexen, C. T., Franz, C., Møller, N. C., Froberg, K., & Wedderkopp, N. (2015). Musculoskeletal extremity injuries in a cohort of schoolchildren aged 6-12: A 2.5-year prospective study. *Scandinavian Journal of Medicine & Science in Sports*, 25(2), 251–8. <http://doi.org/10.1111/sms.12177>
- Johnson, A., Doherty, P. J., & Freemont, A. (2009). Investigation of growth, development, and factors associated with injury in elite schoolboy footballers: prospective study. *BMJ*, 338, b490. <http://doi.org/10.1136/bmj.b490>
- Junge, T., Balsnes, S., Runge, L., Juul-Kristensen, B., & Wedderkopp, N. (2012). Single leg mini squat: an inter-tester reproducibility study of children in the age of 9–10 and 12–14 years presented by various methods

- of kappa calculation. *BMC Musculoskeletal Disorders*, 13, 203.
- Kari, J. T., Tammelin, T. H., Viinikainen, J., Hutri-Kähönen, N., Raitakari, O. T., & Pehkonen, J. (2016). Childhood physical activity and adulthood earnings. *Medicine & Science in Sports & Exercise*, 48(7), 1340–6. <http://doi.org/10.1249/MSS.0000000000000895>
- Kemper, G. L. J., van Der Sluis, A., Brink, M. S., Visscher, C., Frencken, W. G. P., & Elferink-Gemser, M. T. (2015). Anthropometric injury risk factors in elite-standard youth soccer. *International Journal of Sports Medicine*, 36(13), 1112–17. <http://doi.org/10.1055/s-0035-1555778>
- Khuu, A., Foch, E., & Lewis, C. L. (2016). Not all single leg squats are equal: a biomechanical comparison of three variations. *International Journal of Sports Physical Therapy*, 11(2), 201–11.
- Kiesel, K., Plisky, P. J., & Voight, M. L. (2007). Can serious injury in professional football be predicted by a preseason Functional Movement Screen? *North American Journal of Sports Physical Therapy*, 2(3), 147–58. <http://doi.org/10.1186/2052-1847-5-11>
- Kilding, A. E., Tunstall, H., & Kuzmic, D. (2008). Suitability of FIFA’s “The 11” training programme for young football players - impact on physical performance. *Journal of Sports Science and Medicine*, 7(3), 320–26. <http://doi.org/10.3233/IES-2010-0386>
- King, M. A., Pickett, W., & King, A. J. C. (1998). Injury in Canadian youth: A secondary analysis of the 1993-94 Health Behaviour in School-Aged Children Survey. *Canadian Journal of Public Health*, 89(6), 397–401.
- Kjønniksen, L., Anderssen, N., & Wold, B. (2009). Organized youth sport as a predictor of physical activity in adulthood. *Scandinavian Journal of Medicine & Science in Sports*, 19(5), 646–54. <http://doi.org/10.1111/j.1600-0838.2008.00850.x>
- Knapik, J. ., Bauman, C. ., Jones, B. ., Harris, J. ., & Vaughan, L. (1991). Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *American Journal of Sports Medicine*, 19(1), 76–81.
- Knowles, S. B., Marshall, S. W., Miller, T., Spicer, R., Bowling, J. M., Loomis, D., ... Mueller, F. O. (2007). Cost of injuries from a prospective cohort study of North Carolina high school athletes. *Injury Prevention*, 13(6), 416–21. <http://doi.org/10.1136/ip.2006.014720>
- Koivusilta, L., Nupponen, H., & Rimpelä, A. (2012). Adolescent physical activity predicts high education and socio-economic position in adulthood. *European Journal of Public Health*, 22(2), 203–9. <http://doi.org/10.1093/eurpub/ckr037>
- Kreighbaum, E., & Barthels, K. (1985). *Biomechanics: A qualitative approach for studying human movement* (2nd ed.). New York: Macmillan.
- Krivickas, L. S., & Feinberg, J. H. (1996). Lower extremity injuries in college

- athletes: Relation between ligamentous laxity and lower extremity muscle tightness. *Archives of Physical Medicine and Rehabilitation*, 77(11), 1139–43.
[http://doi.org/10.1016/S0003-9993\(96\)90137-9](http://doi.org/10.1016/S0003-9993(96)90137-9)
- Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterback, J. R., ... Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball. Video analysis of 39 cases. *American Journal of Sports Medicine*, 35(3), 359–67.
- Kucera, K. L., Marshall, S. W., Kirkendall, D. T., Marchak, P. M., & Garrett Jr, W. E. (2005). Injury history as a risk factor for incident injury in youth soccer. *British Journal of Sports Medicine*, 39(7), 462–6.
<http://doi.org/10.1136/bjsm.2004.013672>
- Lacny, S., Marshall, D. A., Currie, G., Kulin, N. A., Meeuwisse, W. H., Kang, J., & Emery, C. A. (2014). Reality check: the cost-effectiveness of removing body checking from youth ice hockey. *British Journal of Sports Medicine*, 48(17), 1299–305. <http://doi.org/10.1136/bjsports-2014-093493>
- Le Gall, F., Carling, C., & Reilly, T. (2007). Biological maturity and injury in elite youth football. *Scandinavian Journal of Medicine & Science in Sports*, 17(5), 564–72. <http://doi.org/10.1111/j.1600-0838.2006.00594.x>
- Leadbeater, B., Babul, S., Jansson, M., Scime, G., & Pike, I. (2010). Youth injuries in British Columbia: type, settings, treatment and costs, 2003–2007. *International Journal of Injury Control and Safety Promotion*, 17(2), 119–27.
<http://doi.org/10.1080/17457300903564561>
- Leetun, D. T., Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2004). Core stability measures as risk factors for lower extremity injury in athletes. *Medicine & Science in Sports & Exercise*, 36(6), 926–34.
<http://doi.org/10.1249/01.MSS.0000128145.75199.C3>
- Leivo, T., Haavisto, A. K., & Sahraravand, A. (2015). Sports-related eye injuries: The current picture. *Acta Ophthalmologica*, 93(3), 224–231.
<http://doi.org/10.1111/aos.12633>
- Leivo, T., Puusaari, I., & Mäkitie, T. (2007). Sports-related eye injuries: floorball endangers the eyes of young players. *Scandinavian Journal of Medicine & Science in Sports*, 17(5), 556–63. <http://doi.org/10.1111/j.1600-0838.2006.00607.x>
- Leppänen, M., Pasanen, K., Kujala, U., Vasankari, T., Kannus, P., Äyrämö, S., ... Parkkari, J. (2017). Stiff landings are associated with increased ACL injury risk in young female basketball and floorball players. *The American Journal of Sports Medicine*, 45(2), 386–93.
<http://doi.org/10.1177/0363546516665810>
- Leppänen, M., Pasanen, K., Kulmala, J.-P., Kujala, U. M., Krosshaug, T., Kannus, P., ... Parkkari, J. (2016). Knee control and jump-landing technique in young basketball and floorball players. *International Journal of Sports Medicine*, 37(4), 334–8. <http://doi.org/10.1055/s-0035-1565104>

- Levinger, P., Gilleard, W., & Coleman, C. (2007). Femoral medial deviation angle during a one-leg squat test in individuals with patellofemoral pain syndrome. *Physical Therapy in Sport*, 8(4), 163–8.
- Lima, Y. L., Ferreira, V. M. L. M., de Paula Lima, P. O., Bezerra, M. A., de Oliveira, R. R., & Almeida, G. P. L. (2018). The association of ankle dorsiflexion range of motion and dynamic knee valgus: A systematic review and meta-analysis. *Physical Therapy in Sport*, 29(1), 61–9. <http://doi.org/10.1016/j.ptsp.2017.07.003>
- Lindblom, H., Carlford, S., & Hägglund, M. (2018). Adoption and use of an injury prevention exercise program in female football: A qualitative study among coaches. *Scandinavian Journal of Medicine & Science in Sports*, 28(3), 1295–303. <http://doi.org/10.1111/sms.13012>
- Lindblom, H., Waldén, M., Carlford, S., & Hägglund, M. (2014). Implementation of a neuromuscular training programme in female adolescent football: 3-year follow-up study after a randomised controlled trial. *British Journal of Sports Medicine*, 48(19), 1425–30. <http://doi.org/10.1136/bjsports-2013-093298>
- Lindblom, H., Waldén, M., & Hägglund, M. (2012). No effect on performance tests from a neuromuscular warm-up programme in youth female football: A randomised controlled trial. *Knee Surgery, Sports Traumatology, Arthroscopy*, 20(10), 2116–23. <http://doi.org/10.1007/s00167-011-1846-9>
- Lloyd, R. S., & Oliver, J. L. (2012). The Youth Physical Development Model: A new approach to long-term athletic development. *Strength and Conditioning Journal*, 34(3), 61–72. <http://doi.org/10.1519/SSC.0b013e31825760ea>
- Lohmander, L. S., Östenberg, A., Englund, M., & Roos, H. (2004). High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis and Rheumatism*, 50(10), 3145–52. <http://doi.org/10.1002/art.20589>
- Loud, K. J., Micheli, L. J., Bristol, S., Austin, S., & Gordon, C. (2007). Family history predicts stress fracture in active female adolescents. *Pediatrics*, 120(2), e364–72. <http://doi.org/10.1542/peds.2006-2145>
- Lovell, G., Galloway, H., Hopkins, W., & Harvey, A. (2006). Osteitis pubis and assessment of bone marrow edema at the pubic symphysis with MRI in an elite junior male soccer squad. *Clinical Journal of Sport Medicine*, 16(2), 117–22. <http://doi.org/10.1097/00042752-200603000-00006>
- Lysens, R., Steverlynck, A., van den Auweele, Y., Lefevre, J., Renson, L., Claessens, A., & Ostyn, M. (1984). The predictability of sports injuries. *Sports Medicine*, 1(1), 6–10.
- Maclachlan, L., White, S. G., & Reid, D. (2015). Observer rating versus three-dimensional motion analysis of lower extremity kinematics during functional screening tests: a systematic review. *The International Journal of Sports Physical Therapy*, 10(4), 482–92.

- Madigan, D. J., Stoeber, J., Forsdyke, D., Dayson, M., & Passfield, L. (2018). Perfectionism predicts injury in junior athletes: Preliminary evidence from a prospective study. *Journal of Sports Sciences*, 36(5), 545–50. <http://doi.org/10.1080/02640414.2017.1322709>
- Malina, R. M., Bouchard, C., & Bar-Or, O. (2004). Introductory concepts. In *Growth, maturation, and physical activity* (2nd ed., pp. 3–20). Champaign, IL: Human Kinetics.
- Malina, R. M., Morano, P., Barron, M., Miller, S. J., Cumming, S., & Kontos, A. (2006). Incidence and player risk factors for injury in youth football. *Clinical Journal of Sport Medicine*, 16(3), 214–22. <http://doi.org/10.1017/CBO9781107415324.004>
- Markkula, J., & Öörni, E. (Eds.). (2010). *Providing a safe environment for our children and young people. Finland's national action plan for injury prevention among children and youth*. Helsinki: National Institute for Health and Welfare.
- Marshall, D. A., Lopatina, E., Lacny, S., & Emery, C. A. (2016). Economic impact study: Neuromuscular training reduces the burden of injuries and costs compared to standard warm-up in youth soccer. *British Journal of Sports Medicine*, 50(22), 1388–93. <http://doi.org/10.1136/bjsports-2015-095666>
- Mattila, V. M., Parkkari, J., Kannus, P., & Rimpelä, A. (2004). Occurrence and risk factors of unintentional injuries among 12- to 18-year-old Finns - A survey of 8219 adolescents. *European Journal of Epidemiology*, 19(5), 437–44.
- Mattila, V. M., Parkkari, J., Koivusilta, L., Kannus, P., & Rimpelä, A. (2009). Participation in sports clubs is a strong predictor of injury hospitalization: a prospective cohort study. *Scandinavian Journal of Medicine & Science in Sports*, 19(2), 267–73. <http://doi.org/10.1111/j.1600-0838.2008.00800.x>
- Mauntel, T. C., Begalle, R. L., Cram, T. R., Barnett, S. F., Hirth, C. J., Blackburn, T., & Padua, D. A. (2013). The effects of lower extremity muscle activation and passive range of motion on single leg squat performance. *Journal of Strength and Conditioning Research*, 27(7), 1813–23. <http://doi.org/10.1519/JSC.0b013e318276b886>
- Mauntel, T. C., Frank, B. S., Begalle, R. L., Blackburn, J. T., & Padua, D. A. (2014). Kinematic differences between those with and without medial knee displacement during a single-leg squat. *Journal of Applied Biomechanics*, 30(6), 707–12. <http://doi.org/10.1123/jab.2014-0003>
- McCunn, R., aus der Fünter, K., Fullagar, H. H. K., McKeown, I., & Meyer, T. (2016). Reliability and association with injury of movement screens: A critical review. *Sports Medicine*, 46(6), 763–81. <http://doi.org/10.1007/s40279-015-0453-1>
- McCunn, R., & Meyer, T. (2016). Screening for risk factors: if you liked it then you should have put a number on it. *British Journal of Sports Medicine*, 50(21), 1354. <http://doi.org/10.1136/bjsports-2016-096413>

- McGuine, T. A., Greene, J. J., Best, T., & Levenson, G. (2000). Balance as a predictor of ankle injuries in high school basketball players. *Clinical Journal of Sport Medicine*, 10(4), 239–44. <http://doi.org/10.1097/00042752-200010000-00003>
- McGuine, T. A., & Keene, J. S. (2006). The effect of a balance training program on the risk of ankle sprains in high school athletes. *American Journal of Sports Medicine*, 34(7), 1103–11.
- McGuine, T. A., Post, E. G., Hetzel, S. J., Brooks, M. A., Triggsted, S., & Bell, D. R. (2017). A prospective study on the effect of sport specialization on lower extremity injury rates in high school athletes. *The American Journal of Sports Medicine*, 45(12), 2706–12. <http://doi.org/10.1177/0363546517710213>
- McHugh, M. P. (2010). Oversized young athletes: a weighty concern. *British Journal of Sports Medicine*, 44(1), 45–49. <http://doi.org/10.1136/bjsm.2009.068106>
- McHugh, M. P., Tyler, T. F., Tetro, D. T., Mullaney, M. J., & Nicholas, S. J. (2006). Risk factors for noncontact ankle sprains in high school athletes. The role of hip strength and balance ability. *The American Journal of Sports Medicine*, 34(3), 464–70. <http://doi.org/10.1177/0363546505280427>
- McLean, S. G., Walker, K., Ford, K. R., Myer, G. D., Hewett, T. E., & van den Bogert, A. J. (2005). Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *British Journal of Sports Medicine*, 39(6), 355–62. <http://doi.org/10.1136/bjsm.2005.018598>
- Messina, D. F., Farney, W. C., & DeLee, J. C. (1999). The incidence on injury in Texas high school basketball. A prospective study among male and female athletes. *American Journal of Sports Medicine*, 27(3), 294–9.
- Michaud, P.-A., Renaud, A., & Narring, F. (2001). Sports activities related to injuries? A survey among 9-19 year olds in Switzerland. *Injury Prevention*, 7(1), 41–5.
- Mirwald, R. L., Baxter-Jones, A. D. G., Bailey, D. A., & Beunen, G. P. (2002). An assessment of maturity from anthropometric measurements. *Medicine & Science in Sports & Exercise*, 34(4), 689–94. <http://doi.org/10.1097/00005768-200204000-00020>
- Mizner, R. L., Kawaguchi, J. K., & Chmielewski, T. L. (2008). Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *Journal of Orthopaedic & Sports Physical Therapy*, 38(6), 353–61. <http://doi.org/10.2519/jospt.2008.2726>
- Mokha, M., Sprague, P. A., & Gatens, D. R. (2016). Predicting musculoskeletal injury in National Collegiate Athletic Association Division II athletes from asymmetries and individual-test versus composite Functional Movement Screen scores. *Journal of Athletic Training*, 51(4), 276–82.

- <http://doi.org/10.4085/1062-6050-51.2.07>
- Moller, M., Attermann, J., Myklebust, G., & Wedderkopp, N. (2012). Injury risk in Danish youth and senior elite handball using a new SMS text messages approach. *British Journal of Sports Medicine*, 46(7), 531–7. <http://doi.org/10.1136/bjsports-2012-091022>
- Mononen, K., Blomqvist, M., Koski, P., & Kokko, S. (2016). Urheilu ja seuraharrastaminen [Sports and participation in sport club activities]. In S. Kokko & A. Mehtälä (Eds.), *Lasten ja nuorten liikuntakäyttäytyminen Suomessa. LIITU-tutkimuksen tuloksia 2016. [The Physical Activity Behaviours of Children and Adolescents. Results of the LIITU study, 2016]* (p. 119). Publications of the National Sports Council 2016:4.
- Munro, A., Herrington, L., & Carolan, M. (2012). Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. *Journal of Sport Rehabilitation*, 21(1), 7–11.
- Murphy, D. F., Connolly, A. J., & Beynnon, B. D. (2003). Risk factors for lower extremity injury: a review of the literature. *British Journal of Sports Medicine*, 37(1), 13–29. <http://doi.org/10.1136/bjsm.37.1.13>
- Myer, G. D., Brent, J. L., Ford, K. R., & Hewett, T. E. (2011). Real-time assessment and neuromuscular training feedback techniques to prevent anterior cruciate ligament injury in female athletes. *Strength and Conditioning Journal*, 33(3), 21–35. <http://doi.org/10.1519/SSC.0b013e318213afa8>
- Myer, G. D., Faigenbaum, A. D., Ford, K. R., Best, T. M., Bergeron, M. F., & Hewett, T. E. (2011). When to initiate integrative neuromuscular training to reduce sport-related injuries in youth? *Current Sports Medicine Reports*, 10(3), 155–66. <http://doi.org/10.1016/j.biotechadv.2011.08.021>. Secreted
- Myer, G. D., Ford, K. R., Barber Foss, K. D., Goodman, A., Ceasar, A., Rauh, M. J., ... Hewett, T. E. (2010). The incidence and potential pathomechanics of patellofemoral pain in female athletes. *Clinical Biomechanics*, 25(7), 700–7. <http://doi.org/10.1016/j.clinbiomech.2010.04.001>
- Myer, G. D., Ford, K. R., & Hewett, T. E. (2004). Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *Journal of Athletic Training*, 39(4), 352–64.
- Myer, G. D., Ford, K. R., Paterno, M. V., Nick, T. G., & Hewett, T. E. (2008). The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. *American Journal of Sports Medicine*, 36(6), 1073–80. <http://doi.org/10.1177/0363546507313572>
- Møller, M., Nielsen, R. O., Attermann, J., Wedderkopp, N., Lind, M., Sørensen, H., & Myklebust, G. (2017). Handball load and shoulder injury rate: a 31-week cohort study of 679 elite youth handball players. *British Journal of Sports Medicine*, 51(4), 231–7. <http://doi.org/10.1136/bjsports-2016-096927>

- Møller, M., Wedderkopp, N., Myklebust, G., Lind, M., Sørensen, H., Hebert, J. J., ... Attermann, J. (2018). Validity of the SMS, Phone, and medical staff Examination sports injury surveillance system for time-loss and medical attention injuries in sports. *Scandinavian Journal of Medicine and Science in Sports*, 28(1), 252–259. <http://doi.org/10.1111/sms.12869>
- Nakagawa, T. H., Moriya, É. T. U., Maciel, C. D., & Serrão, F. V. (2012). Trunk, pelvis, hip, and knee kinematics, hip strength, and gluteal muscle activation during a single-leg squat in males and females with and without patellofemoral pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy*, 42(6), 491–501. <http://doi.org/10.2519/jospt.2012.3987>
- Nauta, J., Martin-Diener, E., Martin, B. W., van Mechelen, W., & Verhagen, E. (2015). Injury risk during different physical activity behaviours in children: A systematic review with bias assessment. *Sports Medicine*, 45(3), 327–36. <http://doi.org/10.1007/s40279-014-0289-0>
- Nilstad, A., Bahr, R., & Andersen, T. (2014). Text messaging as a new method for injury registration in sports: A methodological study in elite female football. *Scandinavian Journal of Medicine and Science in Sports*, 24(1), 243–249. <http://doi.org/10.1111/j.1600-0838.2012.01471.x>
- Nilstad, A., Krosshaug, T., Mok, K.-M., Bahr, R., & Andersen, T. E. (2015). Association between anatomical characteristics, knee laxity and muscle strength, and peak knee valgus during vertical drop jump landings. *Journal of Orthopaedic & Sports Physical Therapy*, 45(12), 1–26. <http://doi.org/10.2519/jospt.2015.5612>
- Noehren, B., Davis, I., & Hamill, J. (2007). ASB Clinical Biomechanics Award Winner 2006. Prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clinical Biomechanics*, 22(9), 951–6. <http://doi.org/10.1016/j.clinbiomech.2007.07.001>
- Noyes, F. R., Barber-Westin, S. D., Fleskenstein, C., Walsh, C., & West, J. (2005). The drop-jump screening test: difference in lower limb control by gender and effect of neuromuscular training in female athletes. *American Journal of Sports Medicine*, 33(2), 197–207. <http://doi.org/10.1177/0363546504266484>
- Noyes, F. R., Barber-Westin, S. D., Smith, S. T., & Campbell, T. (2011). A training program to improve neuromuscular indices in female high school volleyball players. *Journal of Strength and Conditioning Research*, 25(8), 2151–60. <http://doi.org/10.1519/JSC.0b013e3181f906ef>
- O’Kane, J. W., Neradilek, M., Polissar, N., Sabado, L., Tencer, A., & Schiff, M. A. (2017). Risk factors for lower extremity overuse injuries in female youth soccer players. *Orthopaedic Journal of Sports Medicine*, 5(10), 2325967117733963. <http://doi.org/10.1177/2325967117733963>
- O’Kane, J. W., Tencer, A., Neradilek, M., Polissar, N., Sabado, L., & Schiff, M. (2015). Is knee separation during a drop jump associated with lower

- extremity injury in adolescent female soccer players? *The American Journal of Sports Medicine*, 44(2), 318–23. <http://doi.org/10.1177/0363546515613076>
- Olsen, O. E., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball. A systematic video analysis. *American Journal of Sports Medicine*, 32(4), 1002–12.
- Padua, D. A., DiStefano, L. J., Beutler, A. I., De La Motte, S. J., DiStefano, M. J., & Marshall, S. W. (2015). The Landing Error Scoring System as a screening tool for an anterior cruciate ligament injury-prevention program in elite-youth soccer athletes. *Journal of Athletic Training*, 50(6), 589–95. <http://doi.org/10.4085/1062-6050-50.1.10>
- Padua, D. A., Marshall, S. W., Boling, M. C., Thigpen, C. A., Garrett, W. E. J., & Beutler, A. I. (2009). The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics. The JUMP-ACL study. *American Journal of Sports Medicine*, 37(10), 1996–2002.
- Parkkari, J., Kujala, U. M., & Kannus, P. (2001). Is it possible to prevent sports injuries? Review of controlled clinical trials and recommendations for future work. *Sports Medicine*, 31(14), 985–95.
- Pasanen, K., Ekola, T., Vasankari, T., Kannus, P., Heinonen, A., Kujala, U. M., & Parkkari, J. (2017). High ankle injury rate in adolescent basketball: A 3-year prospective follow-up study. *Scandinavian Journal of Medicine & Science in Sports*, 27(6), 643–9. <http://doi.org/10.1111/sms.12818>
- Pasanen, K., Hietamo, J., Vasankari, T., Kannus, P., Heinonen, A., Kujala, U. M., ... Parkkari, J. (2018). Acute injuries in Finnish junior floorball league players. *Journal of Science and Medicine in Sport*, 21(3), 268–73. <http://doi.org/10.1016/j.jsams.2017.06.021>
- Pasanen, K., Parkkari, J., Kannus, P., Rossi, L., Palvanen, M., Natri, A., & Järvinen, M. (2008). Injury risk in female floorball: a prospective one-season follow-up. *Scandinavian Journal of Medicine & Science in Sports*, 18(1), 49–54. <http://doi.org/10.1111/j.1600-0838.2007.00640.x>
- Perkins, D. F., Jacobs, J. E., Barber, B. L., & Eccles, J. S. (2004). Childhood and adolescent sports participation as predictors of participation in sports and physical fitness activities during young adulthood. *Youth & Society*, 35(4), 495–520. <http://doi.org/10.1177/0044118X03261619>
- Peterson, L., Junge, A., Chomiak, J., Graf-Baumann, T., & Dvorak, J. (2000). Incidence of football injuries and complaints in different age groups and skill-level groups. *The American Journal of Sports Medicine*, 28(5), S51–7. <http://doi.org/10.1177/28.suppl>
- Pickett, W., Molcho, M., Simpson, K., Janssen, I., Kuntsche, E., Mazur, J., ... Boyce, W. F. (2005). Cross national study of injury and social determinants in adolescents. *Injury Prevention*, 11(4), 213–8. <http://doi.org/10.1136/ip.2004.007021>

- Plisky, P. J., Rauh, M. J., Kaminski, T. W., & Underwood, F. B. (2006). Star excursion balance test as a predictor of lower extremity injury in high school basketball players. *Journal of Orthopaedic & Sports Physical Therapy*, 36(12), 911–9. <http://doi.org/10.2519/jospt.2006.2244>
- Pollard, C. D., Sigward, S. M., & Powers, C. M. (2010). Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics*, 25(2), 142–6. <http://doi.org/10.1016/j.clinbiomech.2009.10.005>
- Portney, L., & Watkins, M. (2009). *Foundations of clinical research: applications to practice* (3. ed, Vol. 3rd). Upper Saddle River (N.J.): Pearson/Prentice Hall. Retrieved from <https://tamcat-finna-fi.helios.uta.fi/Record/tamcat.480842>
- Post, E. G., Bell, D. R., Trigsted, S. M., Pfaller, A. Y., Hetzel, S. J., Brooks, M. A., & McGuine, T. A. (2017). Association of competition volume, club sports, and sport specialization with sex and lower extremity injury history in high school athletes. *Sports Health*, 9(6), 518–23. <http://doi.org/10.1177/1941738117714160>
- Post, E. G., Trigsted, S. M., Riekens, J. W., Hetzel, S., McGuine, T. A., Brooks, M. A., & Bell, D. R. (2017). The association of sport specialization and training volume with injury history in youth athletes. *American Journal of Sports Medicine*, 45(6), 1405–12. <http://doi.org/10.1177/0363546517690848>
- Poulsen, D. R., & James, C. R. (2011). Concurrent validity and reliability of clinical evaluation of the single leg squat. *Physiotherapy Theory and Practice*, 27(8), 586–94. <http://doi.org/10.3109/09593985.2011.552539>
- Powell, J. W., & Barber-Foss, K. D. (2000). Sex-related injury patterns among selected high school sports. *The American Journal of Sports Medicine*, 28(3), 385–91. <http://doi.org/10.1177/036354659302100322>
- Powers, C. M. (2003). The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *Journal of Orthopaedic & Sports Physical Therapy*, 33(11), 639–46. <http://doi.org/10.2519/jospt.2003.33.11.639>
- Powers, C. M. (2010). The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *The Journal of Orthopaedic & Sports Physical Therapy*, 40(2), 42–51. <http://doi.org/10.2519/jospt.2010.3337>
- Quatman, C. E., & Hewett, T. E. (2009). The anterior cruciate ligament injury controversy: is “valgus collapse” a sex-specific mechanism? *British Journal of Sports Medicine*, 43(5), 328–35.
- Quatman, C. E., Quatman-Yates, C. C., & Hewett, T. E. (2010). A “plane” explanation of anterior cruciate ligament injury mechanisms: a systematic review. *Sports Medicine*, 40(9), 729–46. <http://doi.org/10.2165/11534950-000000000-00000>

- Rae, K., Britt, H., Orchard, J., & Finch, C. F. (2005). Classifying sports medicine diagnoses: A comparison of the International classification of diseases 10-Australian modification (ICD-10-AM) and the Orchard sports injury classification system (OSICS-8). *British Journal of Sports Medicine*, 39(12), 907–11. <http://doi.org/10.1136/bjsm.2004.017517>
- Ramirez M, Schaffer KB, Shen H, Kashani S, & Kraus JF. (2006). Injuries to high school football athletes in California. *American Journal of Sports Medicine*, 34(7), 1147–58. <http://doi.org/doi:10.1177/0363546505284385>
- Read, P. J., Oliver, J. L., De Ste Croix, M. B. A., Myer, G. D., & Lloyd, R. S. (2015). Injury risk factors in male youth soccer players. *Strength and Conditioning Journal*, 37(5), 1–7.
- Read, P. J., Oliver, J. L., De Ste Croix, M. B. A., Myer, G. D., & Lloyd, R. S. (2016). Neuromuscular risk factors for knee and ankle ligament injuries in male youth soccer players. *Sports Medicine*. <http://doi.org/10.1007/s40279-016-0479-z>
- Read, P. J., Oliver, J. L., De Ste Croix, M. B., Myer, G. D., & Lloyd, R. S. (2018). A prospective investigation to evaluate risk factors for lower extremity injury risk in male youth soccer players. *Scandinavian Journal of Medicine & Science in Sports*, 28(3), 1244 – 51. <http://doi.org/10.1111/sms.13013>
- Richmond, S. A., Kang, J., Doyle-Baker, P. K., Nettel-Aguirre, A., & Emery, C. A. (2016). A school-based injury prevention program to reduce sport injury risk and improve healthy outcomes in youth : a pilot cluster-randomized controlled trial. *Clinical Journal of Sport Medicine*, 26(4), 291–8. <http://doi.org/10.1097/JSM.0000000000000261>
- Royal, S., Kendrick, D., & Coleman, T. (2007). Promoting bicycle helmet wearing by children using non-legislative interventions: systematic review and meta-analysis. *Injury Prevention*, 13(3), 162–7. <http://doi.org/10.1136/ip.2006.013441>
- Rugg, C., Kadoor, A., Feeley, B. T., & Pandya, N. K. (2018). The effects of playing multiple high school sports on National Basketball Association players' propensity for injury and athletic performance. *The American Journal of Sports Medicine*, 46(2), 402–8. <http://doi.org/10.1177/0363546517738736>
- Rumpf, M. C., & Cronin, J. (2012). Injury incidence, body site, and severity in soccer players aged 6–18 years: implications for injury prevention. *Strength and Conditioning Journal*, 34(1), 20–31. <http://doi.org/10.1519/SSC.0b013e31821a9833>
- Rössler, R., Donath, L., Verhagen, E., Junge, A., Schweizer, T., & Faude, O. (2014). Exercise-based injury prevention in child and adolescent sport: a systematic review and meta-analysis. *Sports Medicine*, 44, 1733–48.

- <http://doi.org/10.1007/s40279-014-0234-2>
- Sasaki, S., Tsuda, E., Yamamoto, Y., Maeda, S., Hayashi, Y., Kimura, Y., ... Ishibashi, Y. (2013). Change with increasing age in control of the lower limbs during jump-landing in adolescents: A 5-year prospective study. *Journal of Orthopaedic Science*, 18(5), 774–81. <http://doi.org/10.1007/s00776-013-0420-3>
- Schiff, M. A., Mack, C., Polissar, N., Levy, M., Dow, S., & O’Kane, J. W. (2010). Soccer injuries in female youth players: Comparison of injury surveillance by certified athletic trainers and Internet. *Journal of Athletic Training*, 45(3), 238–42.
- Scholtes, S. A., & Salsich, G. B. (2017). A dynamic valgus index that combines hip and knee angles: assessment of utility in females with patellofemoral pain. *International Journal of Sports Physical Therapy*, 12(3), 333–40.
- Schwebel, D. C., Banaszek, M. M., & McDaniel, M. (2007). Brief report: Behavioral risk factors for youth soccer (football) injury. *Journal of Pediatric Psychology*, 32(4), 411–6. <http://doi.org/10.1093/jpepsy/jsl034>
- Schwebel, D. C., & Brezaussek, C. M. (2014). Child development and pediatric sport and recreational injuries by age. *Journal of Athletic Training*, 49(6), 780–5. <http://doi.org/10.4085/1062-6050-49.3.41>.
- Shea, K. G., Pfeiffer, R., Wang, J. H., Curtin, M., & Apel, P. J. (2004). Anterior cruciate ligament injury in pediatric and adolescent soccer players: an analysis of insurance data. *Journal of Pediatric Orthopedics*, 24(6), 623–8. <http://doi.org/10.1097/01241398-200411000-00005>
- Shultz, S. J., Schmitz, R. J., Nguyen, A. D., Chaudhari, A. M., Padua, D. A., McLean, S. G., & Sigward, S. M. (2010). ACL Research Retreat V: an update on ACL injury risk and prevention, March 25-27, 2010, Greensboro, NC. *Journal of Athletic Training*, 45(5), 499–508.
- Smith, C. A., Chimera, N. J., & Warren, M. (2015). Association of Y balance test reach asymmetry and injury in Division I Athletes. *Medicine & Science in Sports & Exercise*, 47(1), 136–41. <http://doi.org/10.1249/MSS.0000000000000380>
- Smith, H. C., Johnson, R. J., Shultz, S. J., Tourville, T., Holterman, L. A., Slauterbeck, J., ... Beynnon, B. D. (2012). A prospective evaluation of the Landing Error Scoring System (LESS) as a screening tool for anterior cruciate ligament injury risk. *The American Journal of Sports Medicine*, 37(3), 1996–2002. <http://doi.org/10.1177/0363546511429776>
- Soligard, T., Grindem, H., Bahr, R., & Andersen, T. E. (2010). Are skilled players at greater risk of injury in female youth football? *British Journal of Sports Medicine*, 44(15), 1118–23. <http://doi.org/10.1136/bjsm.2010.075093>
- Spinks, A. B., & McClure, R. J. (2007). Quantifying the risk of sports injury: a systematic review of activity-specific rates for children under 16 years of

- age. *British Journal of Sports Medicine*, 41(9), 548–57.
<http://doi.org/10.1136/bjsm.2006.033605>
- Steffen, K., Andersen, T. E., & Bahr, R. (2007). Risk of injury on artificial turf and natural grass in young female football players. *British Journal of Sports Medicine*, 41(Suppl 1), i33–7. <http://doi.org/10.1136/bjsm.2007.036665>
- Steffen, K., Bakka, H. M., Myklebust, G., & Bahr, R. (2008). Performance aspects of an injury prevention program: A ten-week intervention in adolescent female football players. *Scandinavian Journal of Medicine & Science in Sports*, 18(5), 596–604. <http://doi.org/10.1111/j.1600-0838.2007.00708.x>
- Steffen, K., Nilstad, A., Krosshaug, T., Pasanen, K., Killingmo, A., & Bahr, R. (2017). No association between static and dynamic postural control and ACL injury risk among female elite handball and football players: A prospective study of 838 players. *British Journal of Sports Medicine*, 51(4), 253–9. <http://doi.org/10.1136/bjsports-2016-097068>
- Stensrud, S., Myklebust, G., Kristianslund, E., Bahr, R., & Krosshaug, T. (2010). Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. *British Journal of Sports Medicine*, 45(7), 589–95.
<http://doi.org/10.1136/bjsm.2010.078287>
- Stickler, L., Finley, M., & Gulgin, H. (2015). Relationship between hip and core strength and frontal plane alignment during a single leg squat. *Physical Therapy in Sport*, 16(1), 66–71. <http://doi.org/10.1016/j.ptsp.2014.05.002>
- Stuart, M. J., & Smith, A. (1995). Injuries in Junior A ice hockey. A three-year prospective study. *The American Journal of Sports Medicine*, 23(4), 458–61.
<http://doi.org/10.1177/036354659502300415>
- Stuart, M. J., Smith, A. M., Malo-Ortiguera, S. A., Fischer, T. L., & Larson, D. R. (2002). A comparison of facial protection and the incidence of head, neck, and facial injuries in junior A hockey players. *The American Journal of Sports Medicine*, 30(1), 39–44.
<http://doi.org/10.1177/03635465020300012001>
- Sundblad, G., Saartok, T., Engström, L. M., & Renström, P. (2005). Injuries during physical activity in school children. *Scandinavian Journal of Medicine & Science in Sports*, 15(5), 313–23.
- Söderman, K., Adolphson, J., Lorentzon, R., & Alfredson, H. (2001). Injuries in adolescent female players in European football: a prospective study over one outdoor soccer season. *Scandinavian Journal of Medicine & Science in Sports*, 11(5), 299–304. <http://doi.org/10.1034/j.1600-0838.2001.110508.x>
- Taimela, S., Kujala, U. M., & Osterman, K. (1990). Intrinsic risk factors and athletic injuries. *Sports Medicine*, 9(4), 205–15.
- Teyhen, D. S., Shaffer, S. W., Lorensen, C. L., Halfpap, J. P., Donofry, D. F., Walker, M. J., ... Childs, J. D. (2012). The Functional Movement Screen:

- A reliability study. *Journal of Orthopaedic & Sports Physical Therapy*, 42(6), 530–40. <http://doi.org/10.2519/jospt.2012.3838>
- Thompson, D., Rivara, F., & Thompson, R. (1994). Helmets for preventing head and facial injuries in bicyclists (Review). *Cochrane Database of Systematic Reviews*, (4).
<http://doi.org/10.1002/14651858.CD001855>. www.cochranelibrary.com
- Tiirikainen, K., Lounamaa, A., Paavola, M., Kumpula, H., & Parkkari, J. (2008). Trend in sports injuries among young people in Finland. *International Journal of Sports Medicine*, 29(6), 529–36. <http://doi.org/10.1055/s-2007-965332>
- Toohy, L. A., Drew, M. K., Cook, J. L., Finch, C. F., & Gaida, J. E. (2017). Is subsequent lower limb injury associated with previous injury? A systematic review and meta-analysis. *British Journal of Sports Medicine*, 51(23), 1670–8. <http://doi.org/10.1136/bjsports-2017-097500>
- Tremblay, M. S., LeBlanc, A. G., Kho, M., Saunders, T., Larouche, R., Colley, R., ... Gorber, S. (2011). Systematic review of sedentary behaviour and health indicators in school-aged children and youth. *International Journal of Behavioral Nutrition and Physical Activity*, 8(1), 98. <http://doi.org/10.1139/apnm-2015-0630>
- Trojian, T. H., & McKeag, D. B. (2006). Single leg balance test to identify risk of ankle sprains. *British Journal of Sports Medicine*, 40(7), 610–3; discussion 613. <http://doi.org/10.1136/bjsm.2005.024356>
- Turbeville, S. D., Cowan, L. D., Asal, N. R., Owen, W. L., & Anderson, M. A. (2003). Risk factors for injury in middle school football players. *The American Journal of Sports Medicine*, 31(2), 276–81. <http://doi.org/10.1177/03635465030310022001>
- Turbeville, S. D., Cowan, L. D., Owen, W. L., Asal, N. R., & Anderson, M. A. (2003). Risk factors for injury in high school football players. *American Journal of Sports Medicine*, 31(6), 974–80. <http://doi.org/10.1177/03635465030310063801>
- Tyler, T., McHugh, M. P., Mirabella, M., Mullaney, M., & Nicholas, S. (2006). Risk factors for noncontact ankle sprains in high school football players. The role of previous ankle sprains and body mass index. *The American Journal of Sports Medicine*, 34(3), 471–5. <http://doi.org/10.1177/0363546505280429>
- Ugalde, V., Brockman, C., Bailowitz, Z., & Pollard, C. D. (2015). Single leg squat test and its relationship to dynamic knee valgus and injury risk screening. *PM & R: The Journal of Injury, Function, and Rehabilitation*, 7(3), 229–35. <http://doi.org/10.1016/j.pmrj.2014.08.361>
- Waldén, M., Hägglund, M., Werner, J., & Ekstrand, J. (2011). The epidemiology of anterior cruciate ligament injury in football (soccer): A review of the

- literature from a gender-related perspective. *Knee Surgery, Sports Traumatology, Arthroscopy*, 19(1), 3–10. <http://doi.org/10.1007/s00167-010-1172-7>
- van der Sluis, A., Elferink-Gemser, M., Coelho-e-Silva, M., Nijboer, J., Brink, M., & Visscher, C. (2014). Sport injuries aligned to peak height velocity in talented pubertal soccer players. *International Journal of Sports Medicine*, 35(4), 351–5. <http://doi.org/10.1055/s-0033-1349874>
- van Mechelen, W., Hlobil, H., & Kemper, H. (1992). Incidence, severity, aetiology and prevention of sports injuries: a review of concepts. *Sports Medicine*, 14(2), 82–99. <http://doi.org/10.2165/00007256-199214020-00002>
- Wang, H. K., Chen, C. H., Shiang, T. Y., Jan, M. H., & Lin, K. H. (2006). Risk-factor analysis of high school basketball-player ankle injuries: a prospective controlled cohort study evaluating postural sway, ankle strength, and flexibility. *Archives of Physical Medicine and Rehabilitation*, 87(6), 821–5. <http://doi.org/10.1016/j.apmr.2006.02.024>
- Warren, M., Smith, C. A., & Chimera, N. J. (2015). Association of the Functional Movement Screen with injuries in Division I athletes. *Journal of Sport Rehabilitation*, 24(2), 163–70. <http://doi.org/10.1123/jsr.2013-0141>
- Watson, A., Brickson, S., Brooks, A., & Dunn, W. (2017). Subjective well-being and training load predict in-season injury and illness risk in female youth soccer players. *British Journal of Sports Medicine*, 51(3), 194–9. <http://doi.org/10.1136/bjsports-2016-096584>
- Weeks, B., Carty, C. P., & Horan, S. A. (2012). Kinematic predictors of single-leg squat performance: a comparison of experienced physiotherapists and student physiotherapist. *BMC Musculoskeletal Disorders*, 13, 207. <http://doi.org/10.1186/1471-2474-13-207>
- Weeks, B., Carty, C. P., & Horan, S. A. (2015). Effect of sex and fatigue on single leg squat kinematics in healthy young adults. *BMC Musculoskeletal Disorders*, 16(1), 271. <http://doi.org/10.1186/s12891-015-0739-3>
- Vella, S. A., Cliff, D. P., Okely, A. D., Scully, M. L., & Morley, B. C. (2013). Associations between sports participation, adiposity and obesity-related health behaviors in Australian adolescents. *International Journal of Behavioral Nutrition and Physical Activity*, 10, 113. <http://doi.org/10.1186/1479-5868-10-113>
- Verhagen, E., Bolling, C., & Finch, C. F. (2015). Caution this drug may cause serious harm! Why we must report adverse effects of physical activity promotion. *British Journal of Sports Medicine*, 49(1), 1–2. <http://doi.org/10.1136/bjsports-2014-093604>
- Verhagen, E., Collard, D. C. M., Chin A Paw, M., & van Mechelen, W. (2009). A prospective cohort study on physical activity and sports-related injuries in 10-12-year-old children. *British Journal of Sports Medicine*, 43(13), 1031–5.

- <http://doi.org/10.1136/bjsm.2008.055483>
- Verrelst, R., Willems, T. M., De Clercq, D., Roosen, P., Goossens, L., & Witvrouw, E. (2014). The role of hip abductor and external rotator muscle strength in the development of exertional medial tibial pain: A prospective study. *British Journal of Sports Medicine*, 48(21), 1564–9. <http://doi.org/10.1136/bjsports-2012-091710>
- Vescovi, J. D., & VanHeest, J. L. (2010). Effects of an anterior cruciate ligament injury prevention program on performance in adolescent female soccer players. *Scandinavian Journal of Medicine & Science in Sports*, 20(3), 394–402. <http://doi.org/10.1111/j.1600-0838.2009.00963.x>
- Whatman, C., Hing, W., & Hume, P. (2012). Physiotherapist agreement when visually rating movement quality during lower extremity functional screening tests. *Physical Therapy in Sport*, 13(2), 87–96. <http://doi.org/10.1016/j.ptsp.2011.07.001>
- Whatman, C., Hume, P., & Hing, W. (2013). The reliability and validity of physiotherapist visual rating of dynamic pelvis and knee alignment in young athletes. *Physical Therapy in Sport*, 14(3), 168–74. <http://doi.org/10.1016/j.ptsp.2012.07.001>
- Whittaker, J. L., Woodhouse, L. J., Nettel-Aguirre, A., & Emery, C. A. (2015). Outcomes associated with early post-traumatic osteoarthritis and other negative health consequences 3-10 years following knee joint injury in youth sport. *Osteoarthritis and Cartilage*, 23(7), 1122–9. <http://doi.org/10.1016/j.joca.2015.02.021>
- Wilkerson, G. B., Giles, J. L., & Seibel, D. K. (2012). Prediction of core and lower extremity strains and sprains in collegiate football players: A preliminary study. *Journal of Athletic Training*, 47(3), 264–72. <http://doi.org/10.4085/1062-6050-47.3.17>
- Willson, J., & Davis, I. S. (2008). Utility of the frontal plane projection angle in females with patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy*, 38(10), 606–15. <http://doi.org/10.2519/jospt.2008.2706>
- Willson, J., Ireland, M. L., & Davis, I. (2006). Core strength and lower extremity alignment during single leg squats. *Medicine & Science in Sports & Exercise*, 38(5), 945–52. <http://doi.org/10.1249/01.mss.0000218140.05074.fa>
- Wilson, J., & Jungner, G. (1968). *Principles and practice of screening for disease*. Public Health Papers No. 34. Geneva: World Health Organization. <http://doi.org/10.1001/archinte.1969.00300130131020>
- Visnes, H., & Bahr, R. (2013). Training volume and body composition as risk factors for developing jumper's knee among young elite volleyball players. *Scandinavian Journal of Medicine & Science in Sports*, 23(5), 607–13. <http://doi.org/10.1111/j.1600-0838.2011.01430.x>
- Witchalls, J., Blanch, P., Waddington, G., & Adams, R. (2012). Intrinsic functional deficits associated with increased risk of ankle injuries: a

- systematic review with meta-analysis. *British Journal of Sports Medicine*, 46(7), 515–23. <http://doi.org/10.1136/bjsports-2011-090137>
- World Health Organization. (1986). *Young people's health - a challenge for society : report of a WHO Study Group on Young People and "Health for All by the Year 2000."* Geneva: World Health Organization.
- Yamazaki, J., Muneta, T., Ju, Y. J., & Sekiya, I. (2010). Differences in kinematics of single leg squatting between anterior cruciate ligament-injured patients and healthy controls. *Knee Surgery, Sports Traumatology, Arthroscopy*, 18(1), 56–63.
- Yde, J., & Nielsen, a B. (1990). Sports injuries in adolescents' ball games: soccer, handball and basketball. *British Journal of Sports Medicine*, 24(1), 51–4. <http://doi.org/10.1136/bjism.24.1.51>
- Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007). Deficits in neuromuscular control of the trunk predict knee injury risk. a prospective biomechanical-epidemiologic study. *The American Journal of Sports Medicine*, 35(7), 1123–30. <http://doi.org/10.1177/0363546507301585>
- Zazulak, B. T., Ponce, P. L., Straub, S. J., Medvecky, M. J., Avedisian, L., & Hewett, T. E. (2005). Gender comparison of hip muscle activity during single-leg landing. *The Journal of Orthopaedic & Sports Physical Therapy*, 35(5), 292–9. <http://doi.org/10.2519/jospt.2005.1734>
- Zeller, B., McCrory, J. L., Kibler, W. B., & Uhl, T. L. (2003). Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *American Journal of Sports Medicine*, 31(3), 449–56.
- Åman, M., Forssblad, M., & Henriksson-Larsén, K. (2016). Incidence and severity of reported acute sports injuries in 35 sports using insurance registry data. *Scandinavian Journal of Medicine & Science in Sports*, 26(4), 451–62. <http://doi.org/10.1111/sms.12462>

ORIGINAL PUBLICATIONS

I

**Adolescent physical activity-related injuries in sports club, school sports and
other leisure time physical activities**

by

Räisänen A, Parkkari J, Karhola L, Rimpelä A

2016

Cogent Medicine 2016;3:1260786

Reproduced in accordance with the CC BY 4.0 license



Received: 18 August 2016
Accepted: 09 November 2016
First Published: 17 November 2016

*Corresponding author: Anu M. Räsänen, Tampere Research Center of Sports Medicine, UKK Institute for Health Promotion Research, P.O. Box 30, 33501 Tampere, Finland
E-mail: anu.raisanen@uta.fi

Reviewing editor:
Albert Lee, The Chinese University of Hong Kong, Hong Kong

Additional information is available at the end of the article

SPORTS & EXERCISE | RESEARCH ARTICLE

Adolescent physical activity-related injuries in sports club, school sports and other leisure time physical activities

Anu M. Räsänen^{1*}, Jari Parkkari¹, Lotta Karhola² and Arja Rimpelä^{3,4}

Abstract: *Background:* The objective was to study physical activity (PA)-related injuries in sports club, school sports, and other leisure time PA, and the associations between injuries and PA participation frequency and intensity. *Methods:* A nationally representative sample was obtained and a structured questionnaire was sent. A total of 9,462 Finns (12–18 years) completed the survey. Prevalence of PA-related injuries was gathered by separate questions about sports club injuries, school sports injuries and other leisure time PA injuries. *Results:* Injury prevalence was higher in sports club activities than in other leisure time PA or school sports for boys ($p < 0.001$) and girls ($p < 0.001$). The prevalence of other leisure time injuries was higher than the prevalence of injuries in school sports for boys ($p < 0.001$) and girls ($p < 0.001$). Injuries were associated with higher frequency (OR 10.4, 95% CI 6.7–16.3) and intensity (OR 4.1, 95% CI 2.9–5.8) of PA. *Conclusions:* Out of the three settings, injury prevalence was highest in sports club activities. Higher PA participation frequency and intensity increased the risk of injury. There seems to be a need for further preventative measures to reduce the risks of PA-related injuries, especially in the sports club setting.

Subjects: Physical Education; Youth Sport; Health Promotion; Sports Injury; Quantitative Methods in Sport; Children and Youth

Keywords: adolescent; athletic injuries; exercise; injuries; physical activity

ABOUT THE AUTHORS

This study is part of the Adolescent Health and Lifestyle Survey (AHLS). The AHLS is a nationwide survey system monitoring the health and health-related lifestyle of young people in Finland. The survey has been conducted every second year since 1977. Professor Arja Rimpelä has been the principal investigator of AHLS nearly 30 years. Physical activity has been part of the subjects since very beginning while injuries related to physical activity is a new subject, led by adjunct professor Jari Parkkari. The principal author Anu Räsänen prepares her doctoral thesis on physical activity related injuries and their prevention among adolescents.

PUBLIC INTEREST STATEMENT

Participation in physical activity (PA) provides positive effects on health and wellbeing. The downside of PA is the risk of injury. Adolescents are active in different setting: in sports clubs, schools, and in unorganised activities during leisure time. In sports clubs the proportion of adolescents who get injured is higher than in other settings. But on the other hand, other leisure time PA is more widely practiced. This leads to a high number of injuries even though the proportion of injured adolescents is lower than in sports clubs.

Higher frequency and higher intensity of PA is associated with a higher risk of injuries. There is an urgent need to introduce proven injury prevention measures, such as neuromuscular training, safe equipment and environment in different PA settings.

1. Introduction

Physical activity (PA) in adolescence is associated with various positive outcomes on health, wellbeing, and socio-economic factors. Adolescent PA provides health benefits such as improved bone health (Hallal, Victora, Azevedo, & Wells, 2006), lower blood pressure (Janssen & LeBlanc, 2010), positive changes on the markers of metabolic syndrome (Janssen & LeBlanc, 2010), and lower odds of overweight and obesity (Janssen, Katzmarzyk, Boyce, King, & Pickett, 2004). Adolescent PA also promotes self-esteem (Biddle & Asare, 2011; Hallal et al., 2006) and mental health (Biddle & Asare, 2011). In addition to the positive health effects, PA participation in adolescence predicts higher educational level, higher socio-economic status and higher earnings in adulthood (Kari et al., 2016; Koivusilta, Nupponen, & Rimpelä, 2011). Other important benefits of PA participation are relaxation (van Mechelen et al., 1996), fun, enjoyment, social support, social interaction (Allender, Cowburn, & Foster, 2006) it provides.

Even though sports and recreational activities are generally safe and promote good health, it has been recognized that PA-related injuries have a significant impact on public health (Finch, Wong Shee, & Clapperton, 2014; Schwebel & Brezaussek, 2014). The incidence of PA-related injuries is higher among adolescents than adults (Schmikli, Backx, Kemler, & van Mechelen, 2009), and in the past decades, injury occurrence among young people has increased (Tiirikainen, Lounamaa, Paavola, Kumpula, & Parkkari, 2008). Participation in sports and recreational activities has been identified as a major cause of adolescent injuries (Pickett et al., 2005). In Finland, adolescent sports club participation is the strongest risk factor for injury hospitalization throughout adolescence and early adulthood (Mattila, Parkkari, Koivusilta, Kannus, & Rimpelä, 2009). PA-related injuries also have long term consequences since they can lead to sub-optimal health in later life (Drawer & Fuller, 2001; Kujala, Kaprio, & Sarno, 1994).

Injuries have been reported to be the leading cause why people stop participating in PA (National Center for Disease Control & Prevention, 2002). It has been estimated that annually 8% of adolescents drop out of recreational sporting activities because of injuries or the fear of getting injured (Grimmer, Jones, & Williams, 2000). Reducing the risk of injury increases the likelihood of the continued health benefit (MacKay et al., 2004).

The first step in the sequence of prevention of PA-related injuries is establishing the extent of the injury problem (van Mechelen, Hlobil, & Kemper, 1992). Studies on adolescent PA-related injuries often focus on the individuals who participate in sports in the elite level, while relatively little is known about the injuries that occur in other PA settings. Some prior studies have investigated PA-related injuries in different settings among 6–12-year-old children (Bloemers et al., 2012; Jespersen et al., 2015; Verhagen, Collard, Paw, & van Mechelen, 2009), but we are not aware of previous studies on sports club, school sports and leisure time PA-related injuries on adolescent populations.

In sports club the activities are usually structured and often the focus is on improving the performance in a single sport. In this study school sports cover both the mandatory and self-selected physical education classes (these are mandatory in Finland) and possible student sport activities organised by the school, for example ball games organised during the recess or after school. Other leisure time PA consists of unorganised physical activities, which in Finland can vary by the season, since winter offers very different opportunities for PA summer.

The main objective of this study was to compare the injury rates of 12–18-year-olds in three settings: sports club, school sports and leisure time physical activities. The second aim was to study the association between age and injury prevalence in different settings. Thirdly this study set out to investigate the association between PA-related injuries and PA-participation frequency and exercise intensity. Based on previous studies on younger populations, we hypothesized that there would be more injuries in sports clubs than in other PA settings.

2. Materials and methods

2.1. Data collection

This study is part of the Adolescent Health and Lifestyle Survey (AHLS). The AHLS is a nationwide survey system monitoring the health and health-related lifestyle of young people in Finland. The survey has been conducted every second year since 1977. The survey covers several topics related to adolescent health. Some of the topics alternate and the questions about PA-related injuries were included in the survey in 2009 and 2013. This study reports the combined data from those two years.

In each study year, a nationally representative sample of 12, 14, 16, and 18-year-old Finns born on certain days in June, July, and August was obtained from the Population Register Centre. The dates of birth used in the sampling were selected to ensure the sample included different subjects for each study year. A 12 page structured questionnaire was mailed in February of both study years. Enclosed with the questionnaire the subjects received personal user names and passwords, and information about the option of completing the questionnaire online. Up to three follow-up enquiries were sent to non-respondents. The questionnaire was sent to a total of 19,318 subjects: 9,920 subjects in 2009 and 9,398 subjects in 2013.

2.2. Study participants

In 2009 the number of respondents was 5,516, out of which 2,288 were boys and 3,228 were girls. In 2013, 4,158 responded (1,687 boys and 2,471 girls). For the combined data of 2009 and 2013, the response rate was 50%. A total of 212 subjects were excluded from the analysis due to inconsistencies between their injury information and their PA participation information or information about their student status. In these cases the subject reported no PA participation or being a student but reported an injury in that setting, or vice versa. Out of the 9,462 subjects included in the study, 59% were girls and 41% were boys. The distributions for age groups for boys and girls are presented in Table 1. Participation rates in sports club activities, school sports, and other leisure time PA are presented in Table 2.

2.3. Measurements

2.3.1. PA-related injuries

The injury prevalence refers to the proportion of subjects who had been injured in physical activities during the past twelve months. The injury prevalence's in three settings were based on three questions: "During the past year, have you suffered an injury while participating in sports club activities?", "During the past year have you suffered an injury while participating in a physical education class or instructed student sport?", and "During the past year have you suffered an injury while participating in other leisure time physical activities (not in a sports club)?" In 2009, three options were provided: "No", "Once", and "Twice or more". In 2013, there were four options: "No", "Once", "Twice", and "Three times or more". Due to the different answer options in 2009 and 2013, the injury data were combined to create a dichotomous variable consisting of classes "Not injured" and "Injured at least once". Information about student status was inquired with the question "At the moment, are you a student?" Three options were provided: "No, I'm not a student", "Yes, I am a full time student", and "Yes, I'm a student alongside going to work". In the Finnish education system, physical education is mandatory in comprehensive schools, general upper secondary schools, and vocational schools.

Table 1. Proportions of subjects in age groups by gender

Age (years)	Boys (n = 3,881)		Girls (n = 5,581)	
	%	95% CI	%	95% CI
12	16.5	15.3–17.7	12.4	9.9–14.9
14	30.7	29.2–32.2	29.8	28.6–31.0
16	30.2	28.8–31.6	29.2	28.0–30.4
18	22.6	21.3–23.9	28.6	27.4–29.8

Note: CI = confidence interval.

Table 2. Proportions of subjects participating in sports club activities, school sports and other leisure time physical activities by gender

Physical activity setting	Boys (n = 3,881)		Girls (n = 5,581)	
	%	95% CI	%	95% CI
Sports club activities	52.5	50.8–54.2	47.7	46.3–49.1
School sports	97.2	96.7–97.7	97.4	97.0–97.8
Leisure time PA	95.6	94.9–96.3	97.1	96.6–97.6

Note: CI = confidence interval.

Based on this, it was assumed that all the subjects, who reported being students, participate in school sports (physical education classes and student sports).

The injury prevalence in sports club activities was calculated as a percentage of subjects reporting at least one sports club injury out of subjects reporting participation in sports club activities. The injury prevalence in school sports activities was calculated as a percentage of subjects reporting at least one school sports injury out of subjects reporting being students. The injury prevalence in other leisure time PA was calculated as a percentage of subjects reporting at least one leisure time PA injury out of subjects reporting participation in other leisure time PA.

2.3.2. PA participation and exercise intensity

PA participation levels were derived from two questions: “How often do you participate in sports in your leisure time through sports club training, competitions or games?” and “How often do you participate in PA in other ways in your leisure time?” Seven alternatives were provided: “not at all”, “less often than once a month”, “1–2 times a month”, “approximately once a week”, “2–3 times a week”, “4–5 times a week”, and “approximately every day”. Exercise intensity was determined from the question “When I do sports or PA, usually I experience: no sweating or getting out of breath/some sweating or getting out of breath/moderate sweating or getting out of breath/extensive sweating or getting out of breath/I do not exercise in my leisure time”.

To determine whether exercise intensity was related to injuries, the injuries in sports club, school sports, and other leisure time PA were combined into a new dichotomous variable: “Suffered at least one PA-related injury”. The injury prevalence was calculated as the proportion of subjects reporting at least one injury out of all the subjects.

2.4. Ethics

The study follows the ethical principles of the Declaration of Helsinki. Subjects were informed of the aims, methods, voluntary participation, privacy and confidentiality of the collected information. The study protocol has been approved by the Ethics Committee of Tampere Region (reference Lausunto 2/2010) and the Ethics Committee of the Pirkanmaa Hospital District (reference ETLR06226). Written informed consent was not required.

2.5. Statistical methods

Statistical analyses were performed using the SPSS software (IBM SPSS Statistics Version 23 for Windows). Since some subjects had been injured in more than one PA setting, the groups were not considered to be independent when comparing the injury prevalence between the sports club activities, school sport activities, and other leisure time PA. Therefore McNemar’s test for two related samples was used to test the differences in injury prevalence between PA settings. Pearson’s χ^2 test was used to test differences in the injury prevalence between age groups. Odds ratios (ORs) were used to test for differences in the injury prevalence by sport club participation frequency, other leisure time PA participation frequency and exercise intensity. ORs were obtained from multivariate logistic regression analysis. Age and gender were entered into each multivariate model to adjust for their potential confounding effect. A p -value of <0.05 was considered statistically significant.

3. Results

3.1. Injury prevalence in different settings

Out of the subjects who reported participating in PA in any of the three settings, 32.0% (95% CI, 31.0–33.0) had suffered at least one PA-related injury in the past 12 months. The injury prevalence in sports club activities was 27.5% (95% CI, 25.4–29.6) for boys and 23.8% (95% CI, 22.0–25.6) for girls. In school sports activities, the injury prevalence was 9.8% (95% CI, 8.8–10.8) for boys and 10.0% (95% CI, 9.2–10.8) for girls. In other leisure time PA, the injury prevalence was 17.6% (95% CI, 16.3–18.9) for boys and 13.3% (95% CI, 12.3–14.3) for girls.

According to the McNemar's test for two related samples, the injury prevalence in sports club activities was significantly higher than the injury prevalence in school sports and in other leisure time PA for boys ($p < 0.001$) and girls ($p < 0.001$). The prevalence of other leisure time PA injuries was higher than the prevalence of school sport injuries for boys ($p < 0.001$) and girls ($p < 0.001$).

Pearson's χ^2 test was used to test for differences between age groups. The injury prevalence in sports club, school sports and other leisure time PA by age groups are shown in Figure 1. The injury prevalence varied significantly between the age groups in sports club injuries for boys ($p < 0.05$) and girls ($p < 0.05$). The sports club injury prevalence was highest in the 16 and 18-year-olds among boys

Figure 1. Injury prevalence (%) in sports club activities, school sports and other leisure time physical activities in the past 12 months by age group for boys and girls presented with 95% confidence interval (CI).

Notes: Proportions were calculated from those reporting participation in sports club activities/being students/participation in other leisure time PA. Pearson's χ^2 test was used to test for differences between age groups.

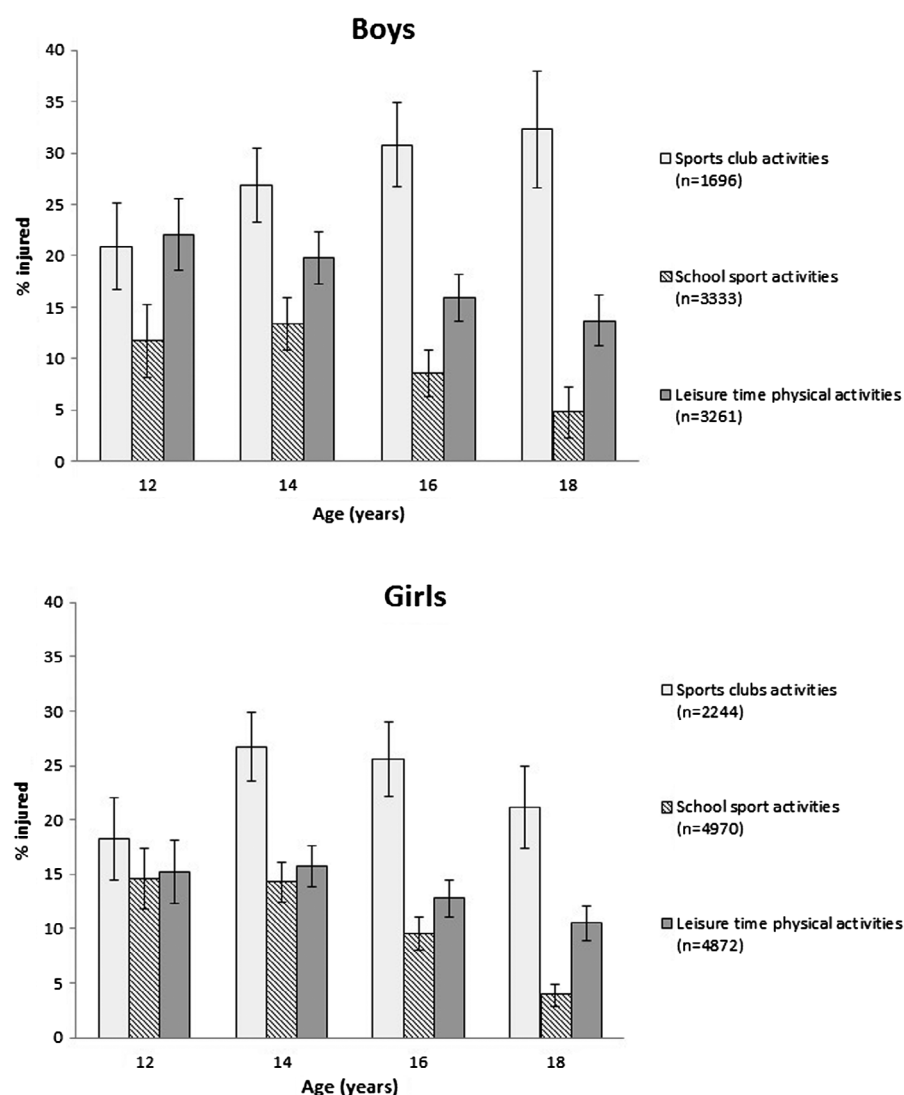


Table 3. Age and gender-adjusted ORs and 95% CIs for sports club injuries by frequency of sports club activity

Frequency of sports club activity	OR	95% CI	p-value
Less than once a month	1		
1–2 Times a month	1.8	1.0–3.1	0.041*
Approximately once/week	1.5	0.9–2.3	0.103
2–3 Times/week	3.1	2.0–4.6	<0.001*
4–5 Times/week	6.9	4.5–10.5	<0.001*
Approximately daily	10.4	6.7–16.3	<0.001*

Note: ORs were derived from multivariate logistic regression analysis.

*Statistical significance based on $p < 0.05$.

and in the 14-year-olds among girls. In school sports and other leisure time PA, the injury prevalence was lowest in the older age groups among boys ($p < 0.001$) and girls ($p < 0.001$).

3.2. Associations between injuries and PA participation and intensity

Multivariate logistic regression analysis was used to test for the associations between injuries and PA participation and intensity. Sports club injuries were associated with the frequency of sports club activities. The odds ratio was highest for those who participated in sports club activities approximately every day (OR 10.4, 95% CI 6.7–16.3). Participating in sports club activities 2–3 times per week or more often significantly increased the risk of sports club injury. The ORs for sports club injuries by participation frequency are presented in Table 3.

The risk for other leisure time PA injuries increased when participation frequency was once a week or higher. The ORs for other leisure time injuries by participation frequency are presented in Table 4.

Table 4. Age and gender-adjusted ORs and 95% CIs for other leisure time injuries by frequency of leisure time physical activity (PA)

Frequency of other leisure time PA	OR	95% CI	p-value
Less than once a month	1		
1–2 Times a month	1.3	0.8–2.2	0.232
Approximately once/week	1.7	1.1–2.6	0.013*
2–3 Times/week	2.1	1.4–3.1	0.001*
4–5 Times/week	2.6	1.7–3.9	<0.001*
Approximately daily	3.1	2.0–4.7	<0.001*

Note: ORs were derived from multivariate logistic regression analysis.

*Statistical significance based on $p < 0.05$.

Table 5. Age and gender-adjusted ORs and 95% CIs for all physical activity-related injuries by intensity of physical activity

Intensity (sweating/getting out of breath)	OR	95% CI	p-value
None	1		
Some	1.6	1.1–2.3	0.009*
Moderate	2.2	1.6–3.2	<0.001*
Extensive	4.1	2.9–5.8	<0.001*

Note: ORs were derived from multivariate logistic regression analysis.

*Statistical significance based on $p < 0.05$.

Exercise intensity was associated with the risk of PA-related injury. Those reporting moderate or extensive sweating/getting out of breath when exercising had 4.1 times higher risk of injury compared to those, who didn't sweat/get out of breath when exercising. The ORs for all PA-related injuries by intensity level are presented in Table 5.

4. Discussion

To our knowledge, this is the first study to compare the injury prevalence in sports club activities, schools sports and other leisure time PA among adolescents. The findings of this study demonstrate that the injury prevalence was significantly higher in sports club activities than in school sports activities and other leisure time PA. In addition, the prevalence of other leisure time PA injuries was higher than the prevalence of school sport injuries. One possible explanation to these differences could be the intensity of PA, since our results also show that exercise intensity was associated with the risk of injury. The sports club PA is structured and the goal is to improve sports performance, therefore it is possibly more intense than other leisure time PA. In school sports the goal is mainly educational and the intensity is likely to be lower than in the other PA settings.

Previous studies on injuries in sports clubs, school sports and other leisure time injuries have been done on school children, aged 12 years and under. Jespersen et al. (2015) studied musculoskeletal injuries among 6–12-year-old Danish school children. They reported the highest rate of traumatic injuries in sports (1.57 injuries/1,000 PA units), followed by leisure time PA (0.57 injuries/1,000 PA units) and PE lessons (0.14 injuries/1,000 PA units). In the iPlay study Verhagen et al. (2009) studied injuries among 10–12 years old Dutch children. The injury incidence density was highest in sports (0.66), followed by PE (0.50) and leisure time PA (0.39). The differences between settings were not significant. Besides these studies focusing on children, direct comparisons are difficult to make due to differences in injury definitions and data collection methods. The common trend in the results of this study and the work of Jespersen et al. (2015) and Verhagen et al. (2009) is that in all the three studies, the prevalence of injuries is highest among sports club activities. Therefore it can be suggested that preventative measures should be introduced more extensively to sports club activities, especially to the sports popular among adolescents.

Among boys the prevalence of sports club injuries increased with age. It has been previously reported that in adolescent sports the intensity and training load increase progressively with age (Malisoux, Frisch, Urhausen, Seil, & Theisen, 2013b). Intensity being associated with the risk of injury, the increase in intensity could explain the increase in boys' injury prevalence. Previous studies suggest that the relation between injuries and age is sport-specific. In a soccer injury study the 16- and 18-year-old boys had lower injury incidence than the 14-year-olds (Emery, Meeuwisse, & Hartmann, 2005). In a hockey injury study the injury incidence increased significantly with age (Emery & Meeuwisse, 2006). In the current study the prevalence of sports club injuries among girls was highest in the 14-year-olds. This is in line with the results of Emery et al. (2005) reporting a higher incidence of soccer injuries among the 14-year-olds than the 16 and 18-year-olds. Sport is one possible factor contributing to the differences in injury prevalence between age groups in this study.

In this study, risk of PA-related injuries increased when the frequency of PA increased. The increase of risk was highest in sports club injuries, where those participating approximately daily had 10.4 times higher risk of injury than those participating less than once a month. This high increase in the risk is somewhat surprising, since there is evidence that training has a protective effect against injury (Gabbett, 2016). In sports, both overtraining and under-training could be linked with a high incidence of injuries (Gabbett, 2016). Under-training is possibly associated with injuries in other PA settings also. In the iPlay-study, Bloemers et al. (2012) studied injuries in leisure time PA, sports and physical education classes in 10–12-year-old children. They demonstrated that the least active children had the highest risk of injury and identified the cut-off level to be 5 h of PA per week. The results of the current study do not support the theory that low levels of participation or under-training increase the risk of injury. It is important to bear in mind that in this study the frequency of sports club activities and other leisure time PA were analysed separately and this could yield different results than using weekly total exposure.

In this study intensity was defined as the level of sweating/getting out of breath during exercise. Sweating and getting out of breath are recommended for adolescents since they need both moderate and vigorous exercise (World Health Organization, 2010). Participating in intense exercise should not be limited by the fear of injury. One possible approach to lowering the risk of injury in intense exercise is developing better movement skills. Neuromuscular training programs aimed to improve movement skills have produced lower injury rates in high intensity sports among adolescent populations (Häggglund, Atroshi, Wagner, & Waldén, 2013; Rössler et al., 2014; Soligard et al., 2008; Wedderkopp, Kaltoft, Lundgaard, Rosendahl, & Froberg, 1999). School-based injury prevention program consisting of neuromuscular training has also been used successfully to reduce the injury risk and at the same time to improve health factors like adiposity and fitness (Richmond, Kang, Doyle-Baker, Nettel-Aguirre, & Emery, 2016). In organized settings, such as sports clubs, another method to lower the injury incidence is implementing an injury surveillance system. Implementing a surveillance system can improve awareness of the problem and further motivate coaching staff to implement preventative measures (Malisoux, Frisch, Urhausen, Seil, & Theisen, 2013a).

In the Finnish education system, physical education classes are mandatory in comprehensive schools, general upper secondary schools, and vocational schools. In this study, the injury prevalence was lower in school sports activities than in other PA settings. However, it could be argued that when participation is mandatory and the goal is educational, the risk of injury should be as low as possible. This result could indicate that further preventative measures should be implemented to lower the injury risk in school sports activities.

The coaches in the sport club activities and the teachers in school sports possess an important role in injury prevention. The coaches, support staff and teachers must enforce rules and the use of safety equipment, such as helmets and protective eye wear when applicable. They must also assess the environmental factors, like weather conditions, and evaluate of the conditions in which equipment are used, such as the apparatus in gymnastics. In addition to these factors load needs to be considered. In sports club coaches should monitor the load individually and make adjustments to training and competition loads if necessary (Soligard et al., 2016). In school sports the teachers should consider that the students most active in physical education lessons are usually active also in sports clubs, other leisure time PA (Trifonov Rexen et al., 2014). Children with low habitual levels of PA are at an increased risk of injury (Nauta, Martin-Diener, Martin, van Mechelen, & Verhagen, 2015). Mandatory physical education classes can be the only form of PA for these children. The teacher has a responsibility to keep the lessons safe for all children and insure that the load is manageable for everyone.

The large, randomly drawn sample can be considered a strength of this study. The response rate to this study was 50%. It has been reported that in survey studies the non-respondents have poorer health behaviour, health and socio-economic background (Pietilä, Rantakallio, & Läärä, 1995). The aim of this study was to compare injury rates in different PA settings in girls and boys of different age groups. Physically active adolescents were expected to respond at a higher rate, and thus, the total response rate was not considered to have a major impact on the reported comparisons.

This study has some limitations. Retrospective, self-reported injury history has the potential for recall bias. However, Gabbe, Finch, Bennell, and Wajswelner (2003) reported that participants were able to correctly indicate whether they had been injured or uninjured in the past 12 months. To minimize the impact of recall bias on the results, we only asked for the injury status and did not request more details, such as the number of injuries, the injured body region, the injury type, the severity or the diagnosis.

In the survey the word “injury” was not defined. It was up to the subject how they perceived the word. Since the purpose of this study was to compare the injury rates in different settings, we believe the lack of detailed injury definition was not necessary, since the subject probably defined injuries similarly in the different settings. It is possible that some minor injuries and overuse injuries have not been reported, and thus, the reported injury rates might slightly underestimate the situation. This is a possible limitation of the study.

Since physical education is mandatory, we interpreted that all subjects reporting to be students participated in schools sports. Since the students' in general upper secondary schools and vocational schools have some freedom to choose when they participate in physical education classes, it is possible that all the 18-year-old students had not participated in PE during the past 12 months. Hence the rate of school sport injuries might be slightly underestimated. This can be seen as a limitation of the study.

According to the "sequence of prevention" the next should be establishing aetiology and mechanisms of injuries (van Mechelen et al., 1992). Therefore in the future it would be beneficial to study in which sports and physical activities the injuries occur. This would provide further information for those working on implementing injury prevention methods. To evaluate the effectiveness of implementation measures and programmes, we recommend regular monitoring of injury prevalence among adolescent population.

5. Conclusions

This study suggests that the rate of PA-related injuries is higher in sports club activities than in other settings of PA among adolescents. Since injury in adolescence can have implications for future participation in PA and also for future health, it is important to introduce preventative measures more extensively, most urgently to the sports club setting. Some caution should be used when interpreting these results since this study is based on self-reported injuries.

This study also suggests that injury rates are associated with PA participation frequency and intensity. It is recommended for health benefits that adolescents participate in PA daily. However our results indicate that participating in PA as little as 2–3 times a week increases the risk of PA-related injury. Since PA participation generates several benefits for health and wellbeing, adolescent PA participation should not be limited due to fear of injury. Instead, the results of this research support the idea that further preventative measures are needed to lower the risk of injury in different settings. To evaluate the effect of preventative measures, it is important to monitor adolescent PA-related injury prevalence and injury settings in regular basis. In the future, it is important to follow PA-related injuries regularly so that a potential increase in injuries can be revealed and preventive measures can be started.

Acknowledgements

We thank Mr Lasse Pere of the School of Health Sciences, University of Tampere, for compiling the data, and we are grateful for the statistical advice of Mr Kari Tokola from the UKK Institute for Health Promotion Research.

Funding

This study was financially supported by the Finnish Ministry of Social Affairs and Health (law on health promotion appropriation); The Finnish Ministry of Education and Culture; The Competitive State Research Funding of the Expert Responsibility Area of Tampere University Hospital [grant number 9P041]; The Foundation of Sports Institute.

Competing Interests

The authors declare no competing interests.

Author details

Anu M. Räsänen¹
E-mail: anu.raisanen@uta.fi
Jari Parkkari¹
E-mail: jari.parkkari@uta.fi
ORCID ID: <http://orcid.org/0000-0001-5211-9845>
Lotta Karhola²
E-mail: karhola.lotta.m@student.uta.fi

Arja Rimpelä^{3,4}

E-mail: arja.rimpela@uta.fi

¹ Tampere Research Center of Sports Medicine, UKK Institute for Health Promotion Research, P.O. Box 30, 33501 Tampere, Finland.

² School of Medicine, University of Tampere, Tampere, Finland.

³ School of Health Sciences and PERLA–Tampere Centre for Childhood, Youth and Family Research, University of Tampere, Tampere, Finland.

⁴ Department of Adolescent Psychiatry, Tampere University Hospital, Tampere, Finland.

Citation information

Cite this article as: Adolescent physical activity-related injuries in sports club, school sports and other leisure time physical activities, Anu M. Räsänen, Jari Parkkari, Lotta Karhola & Arja Rimpelä, *Cogent Medicine* (2016), 3: 1260786.

Authors' contributions

Arja Rimpelä and Jari Parkkari initiated the study. Anu M. Räsänen, Jari Parkkari, Lotta Karhola, and Arja Rimpelä contributed to the study conception and design. Anu M. Räsänen carried out the literature search. Arja Rimpelä conducted the data collection and performed the preliminary data preparations. Anu M. Räsänen and Lotta Karhola conducted the data analyses, and all the authors contributed to the interpretation of data. Anu M. Räsänen,

Jari Parkkari and Arja Rimpelä wrote the first draft of the paper, and all authors provided substantive feedback on the paper and contributed to the final manuscript. All authors have approved the submitted version of the manuscript. Anu M. Räsänen is the guarantor.

References

- Allender, S., Coburn, G., & Foster, C. (2006). Understanding participation in sport and physical activity among children and adults: A review of qualitative studies. *Health Education Research*, 21, 826–835. doi:10.1093/her/cyl063
- Biddle, S. J. H., & Asare, M. (2011). Physical activity and mental health in children and adolescents: A review of reviews. *British Journal of Sports Medicine*, 45, 886–895. doi:10.1136/bjsports-2011-090185
- Bloemers, F., Collard, D., Paw, M. C. A., van Mechelen, W., Twisk, J., & Verhagen, E. (2012). Physical inactivity is a risk factor for physical activity-related injuries in children. *British Journal of Sports Medicine*, 46, 669–674. doi:10.1136/bjsports-2011-090546
- Drawer, S., & Fuller, C. W. (2001). Propensity for osteoarthritis and lower limb joint pain in retired professional soccer players. *British Journal of Sports Medicine*, 35, 402–408. doi:10.1136/bjsm.35.6.402
- Emery, C. A., & Meeuwisse, W. H. (2006). Injury rates, risk factors, and mechanisms of injury in minor hockey. *The American Journal of Sports Medicine*, 34, 1960–1969. doi:10.1177/0363546506290061
- Emery, C. A., Meeuwisse, W. H., & Hartmann, S. E. (2005). Evaluation of risk factors for injury in adolescent soccer: Implementation and validation of an injury surveillance system. *The American Journal of Sports Medicine*, 33, 1882–1891. doi:10.1177/0363546505279576
- Finch, C. F., Wong Shee, A., & Clapperton, A. (2014). Time to add a new priority target for child injury prevention? The case for an excess burden associated with sport and exercise injury: Population-based study. *BMJ Open*, 2014, e005043. doi:10.1136/bmjopen-2014-005043
- Gabbe, B. J., Finch, C. F., Bennell, K. L., & Wajswelner, H. (2003). How valid is a self reported 12 month sports injury history? *British Journal of Sports Medicine*, 37, 545–547. doi:10.1136/bjsm.37.6.545
- Gabbett, T. J. (2016). The training-injury prevention paradox: Should athletes be training smarter and harder? *British Journal of Sports Medicine*, 50, 273–280. doi:10.1136/bjsports-2015-095788
- Grimmer, K. A., Jones, D., & Williams, J. (2000). Prevalence of adolescent injury from recreational exercise: An Australian perspective. *Journal of Adolescent Health*, 27, 266–272. doi:10.1016/S1054-139X(00)00120-8
- Häggglund, M., Atroshi, I., Wagner, P., & Waldén, M. (2013). Superior compliance with a neuromuscular training programme is associated with fewer ACL injuries and fewer acute knee injuries in female adolescent football players: Secondary analysis of an RCT. *British Journal of Sports Medicine*, 47, 974–979. doi:10.1136/bjsports-2013-092644
- Hallal, P. C., Victora, C. G., Azevedo, M. R., & Wells, J. C. K. (2006). Adolescent physical activity and health. *Sports Medicine*, 36, 1019–1030. doi:10.2165/00007256-200636120-00003
- Janssen, I., & LeBlanc, A. G. (2010). Systematic review of the health benefits of physical activity and fitness in school-aged children and youth. *International Journal of Behavioral Nutrition and Physical Activity*, 7, 40. doi:10.1186/1479-5868-7-40
- Janssen, I., Katzmarzyk, P. T., Boyce, W. F., King, M., & Pickett, W. (2004). Overweight and obesity in Canadian adolescents and their associations with dietary habits and physical activity patterns. *Journal of Adolescent Health*, 35, 360–367. doi:10.1016/j.jadohealth.2003.11.095
- Jespersen, E., Rexen, C. T., Franz, C., Møller, N. C., Froberg, K., & Wedderkopp, N. (2015). Musculoskeletal extremity injuries in a cohort of schoolchildren aged 6–12: A 2.5-year prospective study. *Scandinavian Journal of Medicine and Science in Sports*, 25, 251–258. doi:10.1111/sms.12177
- Kari, J. T., Tammelin, T. H., Viinikainen, J., Hutri-Kähönen, N., Raitakari, O. T., & Pehkonen, J. (2016). Childhood physical activity and adulthood earnings. *Medicine and Science in Sports and Exercise*, 48, 1340–1346. doi:10.1249/MSS.0000000000000895
- Koivusilta, L., Nupponen, H., & Rimpelä, A. (2011). Adolescent physical activity predicts high education and socio-economic position in adulthood. *European Journal of Public Health*, 22, 203–209. doi:10.1093/eurpub/ckr037
- Kujala, U. M., Kaprio, J., & Sarno, S. (1994). Osteoarthritis of weight bearing joints of lower limbs in former elite male athletes. *BMJ*, 308, 231–234. doi:10.1136/bmj.308.6923.231
- MacKay, M., Scanlan, A., Olsen, L., Reid, D., Clark, M., McKim, K., & Raina, P. (2004). Looking for the evidence: A systematic review of prevention strategies addressing sport and recreational injury among children and youth. *Journal of Science and Medicine in Sport*, 7, 58–73. doi:10.1016/S1440-2440(04)80045-8
- Malisoux, L., Frisch, A., Urhausen, A., Seil, R., & Theisen, D. (2013a). Injury incidence in a sports school during a 3-year follow-up. *Knee Surgery, Sports Traumatology, Arthroscopy*, 21, 2895–2900. doi:10.1007/s00167-012-2185-1
- Malisoux, L., Frisch, A., Urhausen, A., Seil, R., & Theisen, D. (2013b). Monitoring of sport participation and injury risk in young athletes. *Journal of Science and Medicine in Sport*, 16, 504–508. doi:10.1016/j.jsams.2013.01.008
- Mattila, V. M., Parkkari, J., Koivusilta, L., Kannus, P., & Rimpelä, A. (2009). Participation in sports clubs is a strong predictor of injury hospitalization: A prospective cohort study. *Scandinavian Journal of Medicine and Science in Sports*, 19, 267–273. doi:10.1111/j.1600-0838.2008.00800.x
- National Center for Disease Control and Prevention. (2002). *CDC injury research agenda*. Atlanta, GA: National Center for Injury Prevention and Control.
- Nauta, J., Martin-Diener, E., Martin, B. W., van Mechelen, W., & Verhagen, E. (2015). Injury risk during different physical activity behaviours in children: A systematic review with bias assessment. *Sports Medicine*, 45, 327–336. doi:10.1007/s40279-014-0289-0
- Pickett, W., Molcho, M., Simpson, K., Janssen, I., Kuntsche, E., Mazur, J., ... Boyce, W. F. (2005). Cross national study of injury and social determinants in adolescents. *Injury Prevention*, 11, 213–218. doi:10.1136/ip.2004.007021
- Pietilä, A.-M., Rantakallio, P., & Läärä, E. (1995). Background factors predicting non-response in a health survey of northern Finnish young men. *Scandinavian Journal of Social Medicine*, 23, 129–136. doi:10.1177/140349489502300208
- Richmond, S. A., Kang, J., Doyle-Baker, P. K., Nettel-Aguirre, A., & Emery, C. A. (2016). A school-based injury prevention program to reduce sport injury risk and improve healthy outcomes in youth. *Clinical Journal of Sport Medicine*, 26, 291–298. doi:10.1097/JSM.0000000000000261
- Rössler, R., Donath, L., Verhagen, E. A., Junge, A., Schweizer, T., & Faude, O. (2014). Exercise-based injury prevention in child and adolescent sport: A systematic review and meta-analysis. *Sports Medicine*, 44, 1733–1748. doi:10.1007/s40279-014-0234-2
- Schmikli, S. L., Backx, F. J. G., Kemler, H. J., & van Mechelen, W. (2009). National survey on sports injuries in the Netherlands: Target populations for sports injury prevention programs. *Clinical Journal of Sport Medicine*, 19, 101–106. doi:10.1097/JSM.0b013e31819b9ca3

- Schwebel, D. C., & Brezaussek, C. M. (2014). Child development and pediatric sport and recreational injuries by age. *Journal of Athletic Training*, 49, 780–785. doi:10.4085/1062-6050-49.3.41
- Soligard, T., Myklebust, G., Steffen, K., Holme, I., Silvers, H., Bizzini, M., ... Andersen, T. E. (2008). Comprehensive warm-up programme to prevent injuries in young female footballers: Cluster randomised controlled trial. *BMJ*, 337, a2469. doi:10.1136/bmj.a2469
- Soligard, T., Schwellnus, M., Alonso, J.-M., Bahr, R., Clarsen, B., Dijkstra, H. P., ... Engebretsen, L. (2016). How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *British Journal of Sports Medicine*, 50, 1030–1041. doi:10.1136/bjsports-2016-096572
- Tiirikainen, K., Lounamaa, A., Paaola, M., Kumpula, H., & Parkkari, J. (2008). Trend in sports injuries among young people in Finland. *International Journal of Sports Medicine*, 29, 529–536. doi:10.1055/s-2007-965332
- Trifonov Rexen, C., Andersen, L. B., Ersbøll, A. K., Jespersen, E., Franz, C., & Wedderkopp, N. (2014). Injuries in children with extra physical education in primary schools. *Medicine & Science in Sports & Exercise*, 46, 745–752. doi:10.1249/MSS.0000000000000152
- van Mechelen, W., Hlobil, H., & Kemper, H. (1992). Incidence, severity, aetiology and prevention of sports injuries. *Sports Medicine*, 14, 82–99. doi:10.2165/00007256-199214020-00002
- van Mechelen, W., Twisk, J., Molendijk, A., Blom, B., Snel, J., & Kemper, H. C. (1996). Subject-related risk factors for sports injuries: A 1-yr prospective study in young adults. *Medicine & Science in Sports & Exercise*, 28, 1171–1179. doi:10.1097/00005768-199609000-00014
- Verhagen, E., Collard, D., Paw, M. C. A., & van Mechelen, W. (2009). A prospective cohort study on physical activity and sports-related injuries in 10–12-year-old children. *British Journal of Sports Medicine*, 43, 1031–1035. doi:10.1136/bjsm.2008.055483
- Wedderkopp, N., Kaltoft, M., Lundgaard, B., Rosendahl, M., & Froberg, K. (1999). Prevention of injuries in young female players in European team handball. A prospective intervention study. *Scandinavian Journal of Medicine and Science in Sports*, 9, 41–47. doi:10.1111/j.1600-0838.1999.tb00205.x
- World Health Organization. (2010). *Global recommendations on physical activity for health*. Author. Retrieved from <http://www.ncbi.nlm.nih.gov/books/NBK305057/>



© 2016 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.

You are free to:

Share — copy and redistribute the material in any medium or format
 Adapt — remix, transform, and build upon the material for any purpose, even commercially.
 The licensor cannot revoke these freedoms as long as you follow the license terms.

Under the following terms:

Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made.
 You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.
 No additional restrictions



You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.

Cogent Medicine (ISSN: 2331-205X) is published by Cogent OA, part of Taylor & Francis Group.

Publishing with Cogent OA ensures:

- Immediate, universal access to your article on publication
- High visibility and discoverability via the Cogent OA website as well as Taylor & Francis Online
- Download and citation statistics for your article
- Rapid online publication
- Input from, and dialog with, expert editors and editorial boards
- Retention of full copyright of your article
- Guaranteed legacy preservation of your article
- Discounts and waivers for authors in developing regions

Submit your manuscript to a Cogent OA journal at www.CogentOA.com



II

Single-leg squat as a tool to evaluate young athlete's frontal plane knee control

by

Räisänen A, Pasanen K, Krosshaug T, Avela J, Perttunen J, Parkkari J

2016

Clinical Journal of Sports Medicine 2016;26:478–82.

Reproduced with kind permission by Wolters Kluwer Health, Inc.

Single-leg squat as a tool to evaluate young athletes' frontal plane knee control

Anu Räisänen MHSc,¹ Kati Pasanen PhD,¹ Tron Krosshaug PhD,² Janne Avela PhD,³ Jarmo Perttunen PhD,⁴ Jari Parkkari PhD¹

1) Tampere Research Center of Sports Medicine, UKK Institute for Health Promotion Research, Tampere, Finland

2) Oslo Sports Trauma Research Center, Norwegian School of Sports Sciences, Oslo, Norway

3) NeuroMuscular Research Center, Department of Biology of Physical Activity, University of Jyväskylä, Jyväskylä, Finland

4) Tampere University of Applied Sciences, Tampere, Finland

Corresponding author:

Anu Räisänen MHSc

Tampere Research Center of Sports Medicine, UKK Institute for Health Promotion Research
PO BOX 30, 33501 Tampere, Finland

Tel: +358 3 2829111

Fax: +358 3 2829200

E-mail: anu.raisanen@uta.fi

Word count: 2877 (main text)

Acknowledgements

The authors would like to thank the players, coaches and contact persons of each participating team for their excellent cooperation. We are grateful to physiotherapist Irja Lahtinen (I.L.) for performing the subjective assessments and to statistician Kari Tokola (K.T.) for statistical advice. We greatly acknowledge the collaboration of the Finnish Ministry of Education and Culture and the Competitive State Research Financing of the Expert Responsibility area of Tampere University Hospital for financial support of the study.

Conflicts of interest and sources of funding

This study was funded by the Finnish Ministry of Education and Culture, and the Competitive State Research Financing of the Expert Responsibility area of Tampere University Hospital (Grant 9N053). The funding sources did not have any involvement with the progress of the study. The authors have no conflicts of interest to disclose. The authors have no financial relationships relevant to this article to disclose.

ABSTRACT

Objective: To determine the agreement between 2D video analysis and subjective visual assessment by a physiotherapist in evaluating young athletes' knee control, and to determine the intra- and inter-rater reliability of the single-leg squat test.

Design: Frontal plane knee control was assessed by a physiotherapist on a three-point scale. Frontal plane projection angles were calculated from video images. To determine the intra-rater reliability, a physiotherapist re-assessed 60 subjects' performances from a video. For the inter-rater reliability, 20 subjects were assessed by both the physiotherapist and a non-experienced tester. The study continued for three test years.

Setting: Research institute.

Participants: 378 floorball, basketball, ice hockey and volleyball players.

Assessment of variables: Knee control was assessed to be good, reduced or poor.

Main outcome measures: Agreement between the video analysis and subjectively assessed frontal plane knee control. Intra- and inter-rater reliability.

Results: There were statistically significant differences in the mean frontal plane knee angles between subjects rated as having 'good', 'reduced' or 'poor' knee control. Intra-rater reliability was fair for the assessments in the first year, moderate (dominant leg) and good (non-dominant leg) for the second year, and very good (dominant leg) and good (non-dominant leg) for the third year. Inter-rater reliability was fair/poor.

Conclusions: This study suggests that by using the subjective assessment of the single-leg squat task, it is possible to detect differences in frontal plane knee control in young team sport athletes. The assessment can be considered to be reliable for clinical use when performed by an experienced tester.

Keywords: knee, physiotherapist, evaluation, screening, reliability

INTRODUCTION

Anterior Cruciate Ligament (ACL) injury will often have major consequences in an athlete's life, such as temporary and permanent disability, long-term pain, functional limitations, and absence from school, work or sports (1-3). Post-operative rehabilitation of an ACL injury takes several months and even though many athletes can return to their sport, they return with a higher risk of both re-injury and early retirement from sports (3,4). Furthermore, an ACL injury will also increase the risk of knee instability, meniscus rupture and knee osteoarthritis later in life (5).

In team sports, most ACL injuries occur without player-to-player contact (6-9). Video studies of handball and basketball suggest that the knee valgus collapse may play an important role in ACL rupture (10,11). The dynamic knee valgus is often a combination of knee valgus, hip internal rotation and adduction, tibial rotation and anterior translation, and ankle eversion (12). In a previous study, knee valgus angles and moments have been identified as the primary predictors of ACL injury (13). Individuals with greater strength in hip abductors, knee flexors and knee extensors demonstrate a lower amount of knee valgus in a single-leg squat task (14).

Neuromuscular training programs (which include balance and body control training, strengthening and agility exercises, stretching and running, and cutting and landing techniques) can be effective in reducing the injury incidence among athletes in pivoting sports such as basketball, soccer, team handball and floorball (15-20). It is recommended that programs planned to enhance knee control should focus on avoiding valgus motion. Athletes who demonstrate poor knee control might benefit more from neuromuscular training (21). To screen athletes with poor dynamic knee stability, it is important to test the reliability and validate simple field tests used for screening purposes.

The single-leg squat test is used to screen athletes for poor knee control, for example in pre-participation physical examinations (22). The single-leg squat test simulates an athletic position that requires control of the body over a planted leg that is common in pivoting ball games (23). The visual analysis of knee control during single-leg tasks is used to assess lower limb neuromuscular control (24). Subjective assessment of the single-leg squat performed by a physiotherapist has been found to be a useful screening tool among elite-level and national team handball players (25). In this study, our aim was to find out if this test procedure could also be used reliably among young team sport athletes.

The aim of this study was to determine the agreement between 2D video analysis and subjective visual assessment by a physiotherapist in evaluating knee control among young basketball, floorball, ice hockey and volleyball players. The second aim was to determine the intra-rater reliability of the subjective assessment. Finally, we wanted to determine the inter-rater reliability of the subjective assessment of knee control between a physiotherapist and a non-experienced tester.

METHODS

The single-leg squat test was part of baseline measurements in a prospective cohort study. In this study, one single physiotherapist (I.L.) tested 378 floorball, basketball, ice hockey and volleyball players, out of which 249 were female and 129 were male. The basic characteristics of the subjects and number of subjects from each of the four sports are presented in Table 1.

Subjects participated in the single-leg squat test in spring 2011, spring 2012 or spring 2013. If the subject participated in the test during more than one test period, only the first test was included in the study. Thirteen subjects were unable to name their dominant leg and two subjects were unable to perform the test on their dominant leg due to injury. Subjects' height and weight were measured and the dominant leg was assessed by asking which leg they

would use for take-off in a jump. Participants wore shorts and indoor shoes; female subjects also wore sport tops.

To determine the inter-rater reliability of the subjective assessment between a physiotherapist and a non-experienced tester, we had an inter-rater reliability group of 100 basketball and floorball players who were assessed by the non-experienced tester. This group was formed by randomly dividing the subjects entering the study in 2013 into two groups: the study group and the inter-rater reliability group.

Measurements

The single-leg squat test procedure used in this study is based on the procedure used by Stensrud et al. (25). First, small pieces of sports tape were attached to the left and right anterior superior iliac spine and tuberositas tibiae. All subjects performed 2 x 8 repetitions of two-legged squats and 2 x 5 repetitions of two-legged jumps as a warm-up. A small alteration was made to the original warm-up by leaving out the calf stretches. To standardize the knee flexion angle to 90°, subjects performed a two-legged squat down to 90° of knee flexion. This was measured with a plastic goniometer (Baseline, USA). While the subject was holding this position, a thin rope with a small metallic object in the end was attached to the lateral side of the thigh. The length of the string was adjusted so that in a 90° knee flexion angle, the metallic object was slightly touching the ground. When the subject performed a single-leg squat standing on a metal plate, they could hear the sound of the object touching the plate when they reached 90° knee flexion. All participants were allowed one practice attempt on each leg. The subjects were instructed to hold their hands at their waist and keep their eyes focused straight forward while performing the squat. The trial was deemed invalid if the other leg was held in the front or to the side or if it touched the ground, if the subject fell, if the

subject moved their hands from their waist or if the subject looked down during the trial. All subjects were asked to perform two to three valid trials.

Subjective assessment

The subject's ability to control the knee during the single-leg squat was assessed by the physiotherapist seated in front of the subject. An ordinal scale from 0 to 2 was used. The scale used here has been introduced in a previous study (25). A score of 0 is used for 'good performance' and it was given if the subject displayed no significant lateral tilt of the pelvis, no obvious valgus motion of the knee and no medial/lateral movements or shivering during the performance. A score of 1 corresponds with 'reduced knee control'. Subjects were rated 1 if they displayed some lateral tilt of the pelvis and/or slight valgus movement of the knee and/or some medial/lateral movement or shivering during a trial. Score 2 stands for 'poor performance'. Subjects scored 2 if they displayed lateral tilt of the pelvis and/or a knee moving clearly into a valgus position and/or clear medial/lateral movements of the knee. The subjects were scored by their poorest performance: If only one of the two to three valid trials were assessed as 'poor knee control', the performance was rated 2.

Video analysis

Frontal plane knee angles were assessed for each valid trial. The trials were recorded by the physiotherapist with a digital video camera (HXR-NX70E, Sony, Japan) placed 4.5 meters in front of the metal plate. The video images were analyzed using Java-based computer software (ImageJ, National Institutes of Health, USA). Video analyses were performed by a single researcher (A.R.). From the video image, the greatest knee flexion angle was identified by assessing the subject's lowest pelvis height during the trial. The frontal plane knee angles were then estimated by marking the estimated ankle, knee and hip joint centers in the image.

The mean frontal plane knee angle was calculated from the two to three valid trials for each leg.

Intra-rater and inter-rater reliability of the subjective assessment

Since this study was carried out over three years, the intra-rater reliability was assessed separately for each study year. A sample of 20 subjects per test year was randomly drawn from the video database by a statistician (K.T.), who was not involved in the assessments. These 60 performances were evaluated again by the physiotherapist six months after the third test period had ended. The physiotherapist viewed each performance once from the video recording and rated them using the same ordinal scale used in the initial assessment.

Prior to the study, the physiotherapist trained the non-experienced tester to perform the assessments. First, they went through the written instructions of the test. Secondly, they viewed video recordings of ten subjects, compared their assessments and discussed them. Thirdly, the non-experienced tester assessed performances of 15 subjects simultaneously with the physiotherapist, and the assessments were compared and discussed.

To determine the inter-rater reliability, 20 randomly drawn subjects were assessed by both the non-experienced tester and the physiotherapist. During the third test year, the new subjects entering the study were randomly put in the study group or the inter-rater reliability group. Subjects in the study group were tested by the physiotherapist and subjects in the inter-rater reliability group were tested by the non-experienced tester. The non-experienced tester performed the subjective assessment for 100 subjects. The random sample of 20 subjects was randomly drawn from these subjects. The physiotherapist used the video recordings and viewed the performances of the 20 random subjects once on a 22-inch screen and rated the performances.

Statistical methods

Statistical analyses were performed using SPSS software (IBM SPSS Statistics Version 21 for Windows). One-way ANOVA was used to compare the mean frontal plane knee angles between the subjectively assessed groups. Cohen's kappa test was used to determine the intra-rater and inter-rater reliabilities. Kappa values were defined to be poor if kappa was < 0.20 , fair for values $0.21-0.40$, moderate for $0.41-0.60$, good for $0.61-0.80$ and very good for $0.81-1.00$ (26). Spearman's rank correlation coefficient was used to determine the correlation between the subjective assessment of knee control with the scale of 'good', 'reduced' or 'poor' and the mean frontal plane projection angle (FPPA) measured from the video. A p value < 0.05 was considered statistically significant.

Ethical considerations

All subjects provided written informed consent when entering the study. For subjects younger than 18 years, consent was sought from the legal guardian. The study was approved by the Ethics Committee of Pirkanmaa Hospital District (ETL-code R10169).

RESULTS

Correlation between the FPPAs and subjective assessment

Mean FPPAs measured from the video for the dominant leg for subjects rated 'good', 'reduced' or 'poor' were 2° , 8° and 19° respectively ($p < 0.001$). For the non-dominant leg, mean angles were 1° , 7° and 18° respectively ($p < 0.001$). The mean FPPAs are presented in Table 2. Spearman rank correlation coefficients evaluating the association between the subjective assessment and the FPPAs were 0.64 ($p < 0.001$) for the dominant leg and 0.63 for the non-dominant leg ($p < 0.001$).

Intra-rater reliability for the subjective assessment

The kappa values for the agreement between the physiotherapist's initial assessment and the assessment made using the video recordings were 0.28 (fair) for the dominant leg and 0.29 (fair) for the non-dominant leg for the random sample of 20 subjects from the first test year (Table 3). For the second year sample, the values were 0.60 (moderate) for the dominant leg and 0.64 (good) for the non-dominant leg. For the third year sample, values were 0.89 (very good) for the dominant leg and 0.78 (good) for the non-dominant leg.

Inter-rater reliability for the subjective assessment

Kappa values for the agreement between the assessments by the physiotherapist and the non-experienced tester were 0.32 (fair, $p=0.06$) for the dominant leg (Table 4) and 0.16 (poor, $p=0.35$) for the non-dominant leg (Table 5).

DISCUSSION

The aim of this study was to determine the agreements between 2D video analysis of FPPAs and subjective knee control assessment performed by a physiotherapist. In addition, we wanted to determine the intra-rater reliability of the subjective assessment and the inter-rater reliability between a physiotherapist and a non-experienced tester.

We found that using the subjective assessment of the single-leg squat, it is possible to detect differences in the frontal plane knee angles. The mean FPPAs measured from the video images were statistically different between the subjects rated as 'good', 'reduced' or 'poor' in the physiotherapist's subjective visual assessment.

We also noticed an improvement in the physiotherapist's ability to detect the differences in knee control during the three-year test period. Kappa values for the intra-rater reliability increased from fair in the first year to very good (dominant leg) and good (non-dominant leg)

in the third year. We have estimated that during the first test year, the physiotherapist viewed over 1,000 single-leg squats (each subject performing two to three trials per leg and practice attempts), and the intra-rater reliability for the first year was fair. After the second test year, the physiotherapist had viewed over 2,000 single-leg squats and the intra-rater reliability was moderate/good. Based on this, we could make an estimate that for the non-experienced tester to become experienced enough for the intra-rater reliability to rise to moderate, they need to view and assess over 2,000 single-leg squats. This estimation is based on the data from one physiotherapist, which can be considered a limitation to this study.

We were interested in finding out how well the subjective assessment could be done by a non-experienced tester. The aim was to get information about how well this test could be executed by a person without a physiotherapy degree, for example a coach or an athletics trainer working with young athletes. The inter-rater reliability between the physiotherapist and the non-experienced tester was fair for the dominant leg and poor for the non-dominant leg. Our findings differ from those of a previous study, which concluded that both physiotherapists and inexperienced physiotherapy students can reliably assess the single-leg squat on a ten-point scale (27).

Previous studies with different single-leg squat procedures have been conducted to assess the reliability of the test. The agreement between a physiotherapist and a consensus panel consisting of five clinicians was found to be excellent or substantial depending on the experience level of the physiotherapist (24). When a physiotherapist performed two ratings with a week in between, both times using a video image, the agreement varied from excellent to substantial, again depending on the experience level (24). In a study using a single-leg squat to 60° knee flexion, two investigators rated separately hip adduction and knee valgus during the task. For knee valgus assessment, sensitivity was low to moderate and specificity was moderate to high (28). It seems that the tester's experience level plays an important role

when performing the subjective assessment. This is important to consider when introducing the test for screening use in the field.

A study among Norwegian handball players indicates that the visual assessment of the single-leg squat may be a helpful tool when screening for poor knee control among elite-level athletes (25). The test-retest reliability of single-leg squats was fair for the right leg and moderate for the left leg. The tests were done during the same day so the retest took place after the subjects had performed several maximal strength tests. Consequently, fatigue might have influenced performance in the second test. The intra-rater reliability for the 2D video analysis was assessed in the same study (25). The knee angle difference in measurements done 30 days apart by the same tester was 3.3° (SD 2.9).

In all the subjectively assessed groups, both varus and valgus angles were detected. When assessing the knee control, the observer did not only assess the valgus motion of the knee, but also the medial/lateral movement and shivering. In the greatest knee flexion angle, the knee can be in a varus angle, but during the performance there is clear medial/lateral movement. The subject is assessed as having reduced knee control, but from the video image a very small FPPA is detected. In this study, the FPPA was calculated at the point of the greatest knee flexion angle. This is not necessarily the point of the greatest FPPA, and this can be considered as a limitation to the study. Subjects often demonstrated quite a lot of medial/lateral movement of the knee when descending to the squat but the maximal knee valgus angle can be part of the ascending phase.

In this study, we did not verify the maximal knee flexion angle with an additional video camera. In most cases, the subjects lowered themselves to the squat slowly and began to ascend as soon as they heard the object touching the metal plate. In some cases, subjects performed the single-leg squat task quite fast so that by the time they heard the sound, the

knee flexion angle was slightly smaller than 90°. This could be considered as a limitation to the study.

As mentioned earlier, dynamic knee valgus is a multiplanar motion. In this study, we focused on the frontal plane motion of the knee to allow for easier assessment in the field setting. In the future, we will study if observing and measuring the frontal plane motion is enough to detect the athletes at greater risk of injury.

Conclusions

This study suggests that the subjective assessment of knee control during a single-leg squat task is a suitable tool to screen for athletes with reduced knee control among young team sport athletes, when performed by an experienced tester. In future analyses, we will examine whether those athletes assessed as having poor or reduced control are at greater risk of knee injury.

REFERENCES

- 1 Griffin L, Albohm M, Arendt E, et al. Understanding and preventing noncontact anterior cruciate ligament injuries. A review of the Hunt Valley II meeting, January 2005. *AM J Sports Med* 2006;34:1512-1531.
- 2 Lohmander L, Östenberg A, Englund M, et al. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum* 2004;50:3145-3152.
- 3 Myklebust G, Holm I, Maehlum S, et al. Clinical, functional, and radiologic outcome in team handball players 6 to 11 years after anterior cruciate ligament injury. A follow-up study. *AM J Sports Med* 2003;31:981-989.
- 4 Roos H, Ornell M, Gärdsell P, et al. Soccer after anterior cruciate ligament injury an incompatible combination? A national survey of incidence and risk factors and a 7-year follow-up of 310 players. *Acta Orthop Scand* 1995;66:107-112.
- 5 Gillquist J, Messner K. Anterior cruciate ligament reconstruction and the long term incidence of gonarthrosis. *Sports Med* 1999;27:143-156.
- 6 Agel J, Olson D, Dick R, et al. Descriptive epidemiology of collegiate women's basketball injuries: National Collegiate Athletic Association injury surveillance system, 1988-1989 through 2003-2004. *J Ath Train* 2007;42:202-210.
- 7 Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *AM J Sports Med* 1995;23:694-701.

8 Myklebust G, Maehlum S, Engebretsen L, et al. Registration of cruciate ligament injuries in Norwegian top level team handball. A prospective study covering two seasons. *Scan J Med Sci Sports* 1997;7:289-292.

9 Myklebust G, Maehlum S, Holm I, et al. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scan J Med Sci Sports* 1998;8:149-153.

10 Krosshaug T, Nakamae A, Boden B, et al. Mechanisms of anterior cruciate ligament injury in basketball. Video analysis of 39 cases. *AM J Sports Med* 2007;35:359-367.

11 Olsen O, Myklebust G, Engebretsen L, et al. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *AM J Sports Med* 2004;32:1002-1012.

12 Hewett T, Myer G, Ford K. Anterior cruciate ligament injuries in female athletes. Part 1, mechanisms and risk factors. *AM J Sports Med* 2006;34:299-311.

13 Hewett T, Myer G, Ford K, 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;33:492-501.

14 Claiborne T, Armstrong C, Gandhi V, et al. Relationship between hip and knee strength and knee valgus during a single leg squat. *J App Biom* 2006;22:41-50.

15 Emery C, Meeuwisse W. The effectiveness of a neuromuscular prevention strategy to reduce injuries in youth soccer: a cluster-randomised controlled trial. *Br J Sports Med* 2010;44:555-562.

- 16 Gilchrist J, Mandelbaum B, Melancon H, et al. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *AM J Sports Med* 2008;36:1476-1483.
- 17 LaBella C, Huxford M, Grissom J, et al. Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. *Arch Pediatr Adolesc Med* 2011;165:1033-1040.
- 18 McGuine T, Keene J. The effect of a balance training program on the risk of ankle sprains in high school athletes. *AM J Sports Med* 2006;34:1103-1111.
- 19 Olsen O, Myklebust G, Engebretsen L, et al. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *BMJ* 2005;330(7489):449.
- 20 Pasanen K, : Parkkari J, Pasanen M, et al. Neuromuscular training and the risk of leg injuries in female floorball players: cluster randomised controlled study. *BMJ* 2008;337:a295.
- 21 Ford K, Myer G, Hewett T. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc* 2003;35:1745-1750.
- 22 Parsonage J, Williams R, Rainer P, et al. Assessment of conditioning-specific movement tasks and physical fitness measures in talent identified under 16-year-old Rugby Union players. *J Strength Cond Res* 2014;28:1497-1506.
- 23 Zeller B, McCrory J, Kibler W, et al. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *AM J Sports Med* 2003;31:449-456.

24 Crossley K, Zhang W, Schache A, et al. Performance on the single-leg squat task indicates hip abductor muscle function. *AM J Sports Med* 2011;39:866-873.

25 Stensrud S, Myklebust G, Kristianslund E, et al. Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. *Br J Sports Med* 2010;45:589-595.

26 Altman D. *Practical Statistics for Medical Research*. London: Chapman and Hall 1991.

27 Weeks K, Carty C, Horan S. Kinematic predictors of single-leg squat performance: a comparison of experienced physiotherapists and student physiotherapist. *BMC Musculoskeletal Disorders* 2012;13:207.

28 DiMattia M, Livengood A, Uhl T, et al. What are the validity of the single-leg –squat test and its relationship to hip-abduction strength? . *J Sport Rehabil* 2005;14:108-123.

Table 1. Basic characteristics of subjects and number of participants by sport

Characteristic	Females (n=249)	Males (n=129)
	mean (SD)	mean (SD)
Age (years)	18 (4)	17 (2)
Height (cm)	168 (7)	179 (8)
Weight (kg)	63 (8)	70 (10)
BMI	22 (2)	22 (3)
<hr/>		
Sport	n	n
Floorball	95	70
Basketball	78	59
Ice hockey	58	-
Volleyball	18	-

Table 2. The distribution of athletes in the subjectively assessed groups and the corresponding frontal plane projection angles (°) measured from the video analysis

	Subjective assessment		
	Good	Reduced	Poor
a) dominant leg			
Number of athletes (%)	35 (10)	175 (48)	153 (42)
Measured angles			
Mean (SD)	2.2 (7.3)	7.9 (7.6)	18.7 (8.1) *
Median	2.5	7.6	18.6
Range	-10.1 to 20.2	-16.2 to 31.0	-4.0 to 56.9
b) non-dominant leg			
Number of athletes (%)	33 (9)	173 (47)	159 (44)
Measured angles			
Mean (SD)	1.2 (6.4)	7.5 (6.5)	18.1 (8.7) *
Median	1.0	8.1	19.0
Range	-14.1 to 15.2	-13.8 to 24.1	-6.0 to 38.8

* p<0.001

Table 3. Kappa values for agreement between the physiotherapist's initial assessment and re-assessment (intra-rater reliability)

Test year	Dominant leg		Non-dominant leg	
	Kappa	p-value	Kappa	p-value
1st	0.28	0.06	0.29	0.06
2nd	0.60	<0.01	0.64	<0.001
3rd	0.89	<0.001	0.78	<0.001
All years	0.58	<0.001	0.58	<0.001

Table 4. The agreement between the physiotherapist's and non-experienced tester's assessment of knee control of the dominant leg

Dominant leg	Physiotherapist			Total
	Good	Reduced	Poor	
Non-experienced tester				
Good	0	0	0	0
Reduced	0	5	0	5
Poor	0	7	6	13
Total	0	12	6	18

Cohen's kappa 0.32, p=0.06

Table 5. The agreement between the physiotherapist's and non-experienced tester's assessment of knee control of the non-dominant leg

Non-dominant leg	Physiotherapist			Total
	Good	Reduced	Poor	
Non-experienced tester				
Good	0	0	0	0
Reduced	1	2	6	9
Poor	0	1	8	9
Total	1	3	14	18

Cohen's kappa 0.16, p=0.35

III

Association between frontal plane knee control and lower extremity injuries: A prospective study on young team sport athletes.

by

Räisänen A, Pasanen K, Krosshaug T, Vasankari T, Kannus P, Heinonen A, Kujala
UM, Avela J, Perttunen J, Parkkari J
2018

BMJ Open Sport & Exercise Medicine 2018;4:e000311

Reproduced in accordance with the CC BY-NC 4.0 license

Association between frontal plane knee control and lower extremity injuries: a prospective study on young team sport athletes

Anu M Räisänen,¹ Kati Pasanen,^{2,3} Tron Krosshaug,⁴ Tommi Vasankari,³ Pekka Kannus,³ Ari Heinonen,⁵ Urho M Kujala,⁵ Janne Avela,⁵ Jarmo Perttunen,⁶ Jari Parkkari¹

To cite: Räisänen AM, Pasanen K, Krosshaug T, *et al.* Association between frontal plane knee control and lower extremity injuries: a prospective study on young team sport athletes. *BMJ Open Sport & Exercise Medicine* 2018;**4**:e000311. doi:10.1136/bmjsem-2017-000311

Received 18 October 2017
Revised 9 December 2017
Accepted 14 December 2017



CrossMark

¹Tampere Research Center of Sports Medicine, UKK Institute for Health Promotion Research, Tampere, Finland

²Sport Injury Prevention Research Centre, Faculty of Kinesiology, University of Calgary, Calgary, Alberta, Canada

³UKK Institute for Health Promotion Research, Tampere, Finland

⁴Norwegian School of Sports Sciences, Oslo Sports Trauma Research Center, Oslo, Norway

⁵Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland

⁶Tampere University of Applied Sciences, Tampere, Finland

Correspondence to

Anu M Räisänen; anu.raisanen@uta.fi

ABSTRACT

Background/aim Poor frontal plane knee control can manifest as increased dynamic knee valgus during athletic tasks. The purpose of this study was to investigate the association between frontal plane knee control and the risk of acute lower extremity injuries. In addition, we wanted to study if the single-leg squat (SLS) test can be used as a screening tool to identify athletes with an increased injury risk.

Methods A total of 306 basketball and floorball players participated in the baseline SLS test and a 12-month injury registration follow-up. Acute lower extremity time-loss injuries were registered. Frontal plane knee projection angles (FPKPA) during the SLS were calculated using a two-dimensional video analysis.

Results Athletes displaying a high FPKPA were 2.7 times more likely to sustain a lower extremity injury (adjusted OR 2.67, 95% CI 1.23 to 5.83) and 2.4 times more likely to sustain an ankle injury (OR 2.37, 95% CI 1.13 to 4.98). There was no statistically significant association between FPKPA and knee injury (OR 1.49, 95% CI 0.56 to 3.98). The receiver operating characteristic curve analyses indicated poor combined sensitivity and specificity when FPKPA was used as a screening test for lower extremity injuries (area under the curve of 0.59) and ankle injuries (area under the curve of 0.58).

Conclusions Athletes displaying a large FPKPA in the SLS test had an elevated risk of acute lower extremity and ankle injuries. However, the SLS test is not sensitive and specific enough to be used as a screening tool for future injury risk.

INTRODUCTION

In fast-paced team sports such as football, basketball, handball and floorball, injury incidence is high and adolescents are injured more frequently than children or adults.^{1–6} In these sports, most injuries occur in the lower extremities.^{1–5 7} To reduce the burden of sports injuries, it is essential to identify modifiable risk factors, which can be targeted with injury prevention strategies. Neuromuscular deficiencies, such as poor frontal plane

What are the new findings?

- ▶ Previously healthy athletes, who displayed large frontal plane knee projection angles during the single-leg squat (SLS) test, were 2.7 times more likely to sustain acute lower extremity injuries.
- ▶ Large frontal plane knee projection angles were most clearly associated with acute ankle injuries.
- ▶ Measuring the frontal plane knee projection angles in the SLS test is not sensitive and specific enough to be used as a screening tool.

knee control, are potentially modifiable intrinsic factors and possibly associated with a higher risk of lower extremity injury.^{8 9} Inadequate ability to control knee movement on the frontal plane can manifest as high knee valgus.

To our knowledge, there are no previous studies investigating the association between frontal plane knee projection angle (FPKPA) and lower extremity injuries. Some previous studies have examined the associations between other measurements of knee control and lower extremity injuries. Hewett *et al* demonstrated that among female high school athletes, athletes suffering an anterior cruciate ligament injury during the follow-up demonstrated 2.5 times greater knee abduction moment during a baseline vertical drop jump than athletes who remained uninjured.¹⁰ However, this finding was not supported by studies on adult female football and handball players and young female floorball and basketball players.^{11 12} In young female football players, low normalised knee separation in the vertical drop jump test was associated with a higher risk of acute lower extremity injuries.¹³ The previous studies on knee control are not in agreement but they indicate that the role of knee control on injury risk should be investigated

further. The single-leg squat (SLS) is a movement control test often used in clinical practice and research to assess frontal plane knee control, but it has not been previously studied as a potential screening test.^{14–18}

Two-dimensional (2D) video analysis of the SLS is a reliable tool to measure knee valgus, and it has been validated against the gold standard, three-dimensional (3D) motion analysis.^{19 20} Whereas the 3D analysis is usually costly and performed in a laboratory environment, the 2D method is easy to set up in a field setting. This ease of use, coupled with the lower cost of the analysis, makes the

2D method more feasible for large-scale screenings and was therefore chosen.

The objective of this study was to investigate the association between FPKPA and acute lower extremity injuries in young, previously healthy athletes. In addition to lower extremity injuries, we wanted to explore the association between FPKPA and ankle injuries and knee injuries specifically, as these are the most commonly injured body parts in team sports. Furthermore, we set out to investigate if the SLS test is a suitable screening tool to identify athletes with increased risk of injury.

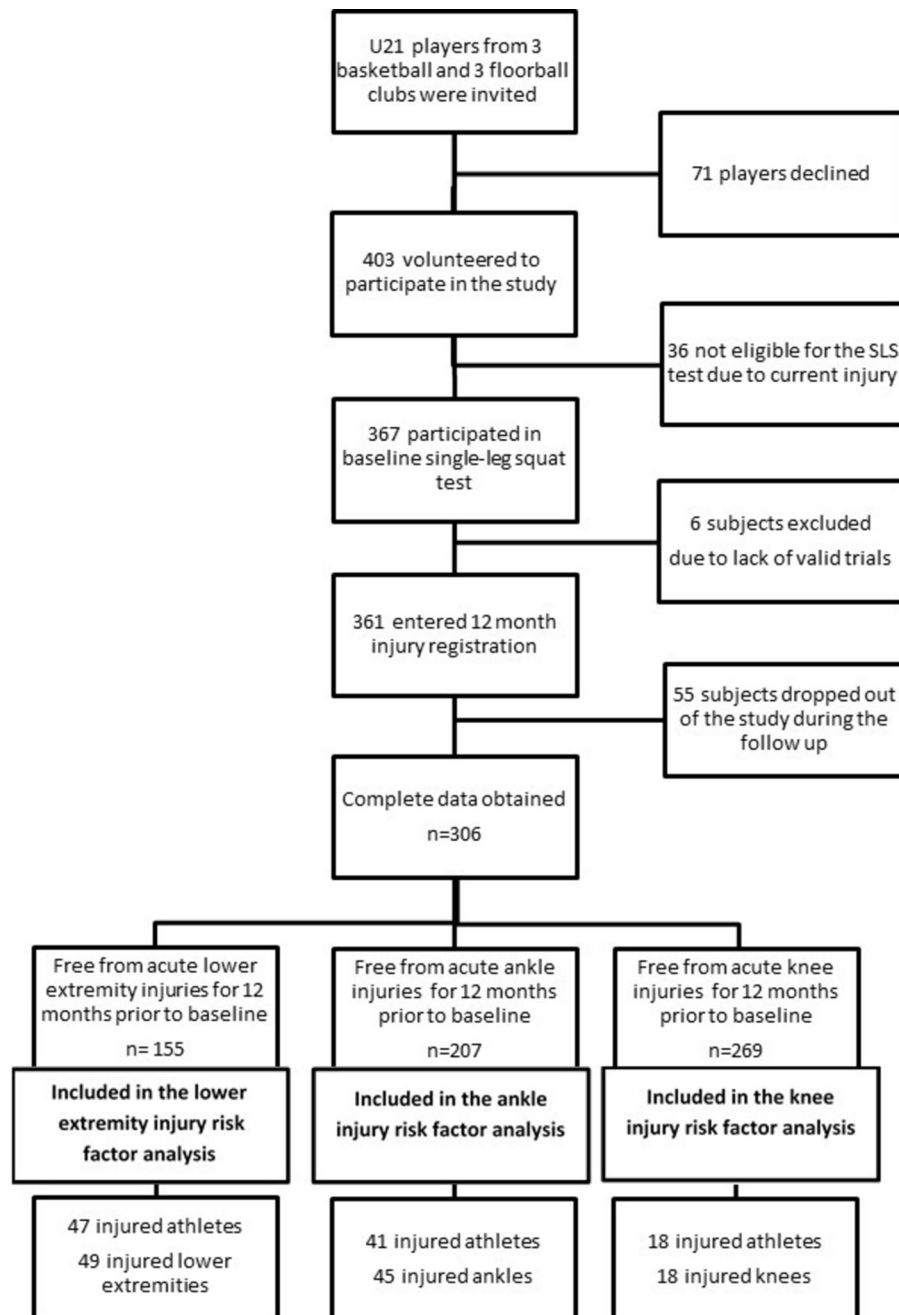


Figure 1 Number of athletes included in the analysis of lower extremity injury risk, ankle injury risk and knee injury risk. Athletes sustaining knee and ankle injuries were also included in the analysis of all lower extremity injuries. SLS, single-leg squat.

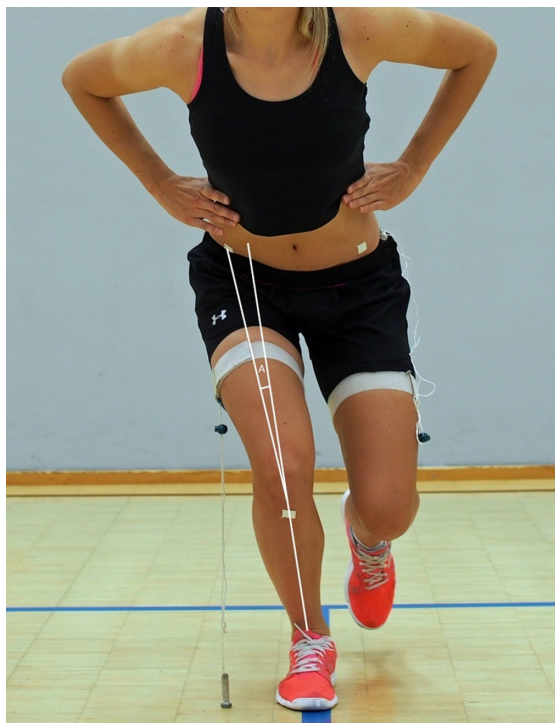


Figure 2 An athlete demonstrating the single-leg squat test. 'A' marks the frontal plane knee projection angle.

MATERIALS AND METHODS

Study design and participants

This study is part of a prospective cohort study (the PROFITS study) and the protocol has been published elsewhere.²¹ Subjects were young basketball and floorball players aged 21 years and under. The data set comprised their personal details (sex, height, weight, exposure, sport played, etc), baseline SLS test results and prospective 1-year injury data. The number of subjects at each stage is presented in [figure 1](#).

Subjects free of lower extremity injury participated in the baseline measurements. A total of 367 athletes participated in the SLS test. Of this number, six athletes were excluded since they did not perform enough valid trials. Subjects provided written informed consent. For subjects younger than 18 years, consent was also sought from a legal guardian.

Baseline measurements

Athletes entered the study during the preseason of 2011, 2012 or 2013. Athletes' height and weight were measured, and body mass index (BMI, kg/m²) was calculated. Athletes filled out a questionnaire on the time-loss injuries they had sustained during the past 12 months.

The SLS test was based on the work of Stensrud *et al*, and the detailed test protocol has been published previously.^{17 21 22} Subjects performed three SLS to 90° knee flexion on each leg. Trials were recorded with a high-definition digital video camera (HXR-NX70E, Sony Japan). The mean FPKPA for each leg from a minimum of two valid squats was calculated from the video footage by the primary investigator (AMR) using a Java-based computer

software (ImageJ, National Institutes of Health). The squat was deemed invalid if the non-weight-bearing leg was held in the front or to the side or it touched the floor or if the player fell, looked down or moved their hands from the waist. The video analysis was conducted blind to past and future injury status. The FPKPA was calculated as the intersection of a line created by the anterior superior iliac spine and knee joint centre and the line created by the knee joint centre and the ankle joint centre. Neutral alignment was considered 0°, positive values represented valgus alignment and negative values represented varus alignment. The measurement of FPKPA is presented in [figure 2](#). The video analysis method has been described in detail previously.²²

Injury definition, and injury and exposure registration

'Injury' was defined as any acute lower extremity (hip, groin, thigh, knee, lower leg, ankle, foot) injury that resulted in an athlete being unable to fully participate in training or match play for at least 24 hours. The injuries were recorded by a team coach or another designated team member. For injury registration, the study physicians and study assistants contacted the teams on a weekly basis. The study physicians contacted the athlete after each injury and collected information about the injury time, place, cause, type, location and the time-loss due to the injury in a standardised phone interview. For exposure registration, the team coaches recorded athlete participation in team practice and match play. After each follow-up month, the coach emailed the participation records to the study group.

Statistical methods

Injury risk does not necessarily increase or decrease linearly; therefore, categorical variables were used in addition to continuous variables.²³ To account for the possibly non-linear association between a variable and injury risk, continuous variables were transformed into categorical variables using the mean averages and SD of the entire cohort.²³ Age, height, weight, BMI, FPKPA, training exposure, match exposure and total exposure were each categorised into three groups: the intermediate reference group (mean±1SD), the low group (values lower than 1 SD below the mean) and the high group (values higher than 1 SD above the mean).

Analyses were performed using SPSS (V.23, SPSS). To compare the athletes injured during the follow-up with the uninjured athletes, the Mann-Whitney U test was used to test the variables that were not normally distributed (age, BMI, exposure variables), the independent samples t test was used for the normally distributed variables (height, weight, FPKPAs) and the χ^2 test was used for the categorical variables (sex, sport).

A generalised linear mixed model for binary data with injury/no injury as the dependent variable was used to analyse the potential risk factors. The generalised linear mixed model was chosen as it allows the use of random effects. Team and leg were used as random

effects. The analyses were performed using each leg as a unit of analysis. To ensure the equal length of exposure period, only athletes who completed the 12-month follow-up were analysed. Only athletes free from lower extremity injuries during the previous year were included in the lower extremity injury risk factor analysis. Similarly, only athletes without ankle or knee injuries were included in the ankle and knee injury risk factor analyses, respectively. The number of athletes included in each analysis is presented in [figure 1](#). ORs, derived from the univariate and multivariate analysis, quantify the association between the factor and the occurrence of injury. First, the baseline risk factors were analysed using the univariate model. All the variables with a P value <0.20 in the univariate analysis were entered into a multivariate model to generate the adjusted ORs. In the multivariate analysis, the significance level was set at P<0.05. Receiver operating characteristic (ROC) curve analyses were performed to analyse the sensitivity and the specificity of the identified risk factors. Area under the curve (AUC) was used to classify the combined sensitivity and specificity as outstanding (0.90–1), excellent (0.80–0.89), acceptable (0.70–0.79), poor (0.51–0.69) and no discrimination (0.50).²⁴

RESULTS

Subjects

Complete data were obtained from 306 athletes (age 15.7±1.8 years, height 173.3±9.1 cm, weight 64.6±10.0 kg), of which 52% were male. The proportions of basketball and floorball players were equal. The mean FPKPA was 13.3±10.5°.

Of the 306 subjects, 155 were free from acute lower extremity (hip, groin, thigh, knee, lower leg, ankle, foot) injury, 207 athletes were free from acute ankle injuries and 269 were free from acute knee injuries for 12 months before entering the study. The 110 injured athletes did not differ from the 196 uninjured athletes by age, height, weight, BMI, gender, sport, training exposure, match exposure or match and training exposure. Athletes sustaining ankle or knee injuries were also analysed in the analysis of all acute lower extremity injuries. The number of athletes at each stage of the study is presented in [figure 1](#).

Risk factors for acute lower extremity injuries

During the 12-month follow-up, 47 of the 155 athletes sustained acute lower extremity injuries. Two athletes had sustained injuries to both legs during the follow-up. In the multivariate model, only a FPKPA greater than 1 SD above the mean (>23.8°) was associated with lower extremity injuries (adjusted OR 2.67, 95% CI 1.23 to 5.83). The ORs from the univariate analysis and the adjusted ORs from the multivariate analysis are presented in [table 1](#).

Risk factors for acute ankle injuries

Of the 207 athletes, 41 suffered acute ankle injuries during the follow-up. Four athletes injured both ankles.

Displaying a FPKPA greater than 1 SD above the mean (>23.8°) in the SLS test was associated with a higher risk of ankle injury (OR 2.37, 95% CI 1.13 to 4.98). Since none of the other variables achieved P<0.20 in the univariate analysis, no multivariate analysis was performed. The ORs for the variables in the univariate analysis are presented in [table 2](#).

Risk factors for acute knee injuries

During the follow-up, 18 knee injuries were recorded for the 269 athletes. No statistically significant associations between the analysed variables and knee injuries were detected. The OR for displaying a FPKPA greater than 1 SD above the mean (>23.8°) in the SLS test was 1.49 (95% CI 0.56 to 3.98), but this was not statistically significant. Since only the categorical variable of age achieved P<0.20 in the univariate analysis, no multivariate analysis was performed. The ORs for the variables in the univariate analysis are presented in [table 3](#).

Specificity and sensitivity analyses

The ROC curve analysis for the FPKPA and lower extremity injuries showed an AUC of 0.59, which indicates poor specificity and sensitivity. For the FPKPA and ankle injuries, the AUC was 0.58, indicating poor specificity and sensitivity. The distribution of the injured and uninjured lower extremities by FPKPA is presented in [figure 3](#). The figure illustrates that there is substantial overlap between the injured and uninjured athletes.

DISCUSSION

FPKPA and injury risk

This study focused on a previously established knowledge gap in the association between the results of a functional movement control test and the risk of lower extremity injury. Our results demonstrate that excessive knee valgus motion during the SLS is associated with lower extremity injuries: athletes displaying a large FPKPA were 2.7 times more likely to sustain a lower extremity injury compared with the athletes displaying intermediate values.

To our knowledge, there are no previous studies examining the association between FPKPA and lower extremity injury risk. Previous studies have hypothesised that knee valgus motion during the SLS test could be related to injury risk and have acknowledged the need to study this association.^{16 20 25} A previous study has linked knee valgus motion during the vertical drop jump test to an increased risk of ACL injuries in adolescents female athletes, but this finding has not been confirmed in later studies.^{10–12} In this study, none of the variables were associated with the risk of knee injuries. However, the small number of injured knees (n=18) could have a considerable influence on why no potential risk factors were identified.

Knee control is a modifiable risk factor

Due to the multifactorial nature of sports injuries, athletes with good knee control do also sustain injuries. However, athletes with poor knee control would

Table 1 ORs for potential lower extremity injury risk factors among young athletes

	OR	95% CI	P value
Univariate analysis			
Categorical variables			
Basketball	1		
Floorball	0.97	0.52 to 1.79	0.92
Female	1		
Male	1.08	0.58 to 1.99	0.81
Age, intermediate (mean±SD)	1		
Age, low (<1 SD below mean,<13.9 years)	1.58	0.72 to 3.50	0.26
Age, high (>1 SD above mean,>17.5 years)	1.35	0.55 to 3.35	0.51
Height, intermediate (mean±SD)	1		
Height, low (<1 SD below mean,<164.2 cm)	0.81	0.35 to 1.87	0.62
Height, high (>1 SD above mean,>182.4 cm)	0.91	0.37 to 2.22	0.83
Weight, intermediate (mean±SD)	1		
Weight, low (<1 SD below mean,<54.7 kg)	0.71	0.28 to 1.79	0.46
Weight, high (>1 SD above mean,>74.6 kg)	0.51	0.17 to 1.50	0.22
BMI, intermediate (mean±SD)	1		
BMI, low (<1 SD below mean,<19.0)	0.99	0.42 to 2.30	0.97
BMI, high (>1 SD above mean,>23.9)	1.14	0.49 to 2.69	0.76
FPKPA, intermediate (mean±SD)	1		
FPKPA, low (<1 SD below mean,<2.7°)	1.12	0.43 to 2.90	0.82
FPKPA, high (>1 SD above mean,>23.8°)	2.55	1.18 to 5.51	0.02*
Training exposure, intermediate (mean±SD)	1		
Training exposure, low (<1 SD below mean,<162.4 hours)	1.33	0.58 to 3.02	0.50
Training exposure, high (>1 SD above mean,>346.0 hours)	0.83	0.30 to 2.28	0.71
Match exposure, intermediate (mean±SD)	1		
Match exposure, low (<1 SD below mean,<3.9 hours)	0.44	0.13 to 1.49	0.19*

Continued

Table 1 Continued

	OR	95% CI	P value
Match exposure, high (>1 SD above mean,>15 hours)	0.69	0.29 to 1.65	0.41
Match and training exposure, intermediate (mean±SD)	1		
Match and training exposure, low (<1 SD below mean,<169.6 hours)	1.19	0.51 to 2.78	0.70
Match and training exposure, high (>1 SD above mean,>357.7 hours)	0.81	0.29 to 2.23	0.68
Continuous variables			
Age (years)	1.04	0.87 to 1.24	0.67
Height (cm)	1.00	0.97 to 1.04	0.85
Weight (kg)	1.00	0.97 to 1.04	0.86
BMI (kg/m ²)	1.01	0.90 to 1.14	0.87
FPKPA (°)	1.01	0.98 to 1.05	0.38
Training exposure (hour)	1.00	1.00 to 1.00	0.95
Match exposure (hour)	0.99	0.94 to 1.05	0.82
Match and training exposure (hour)	1.00	1.00 to 1.00	0.94
Multivariate analysis			
FPKPA>1 SD above mean (>23.8)	2.67	1.23 to 5.83	0.01†

All variables are presented for the univariate analysis, but only variables with a P value<0.05 are presented for the multivariate analysis.

*Variables achieving P<0.20 in the univariate analysis were entered into the multivariate model.

†Only variables achieving P<0.05 in the multivariate model are presented.

BMI, body mass index; FPKPA, frontal plane knee projection angle.

benefit most from neuromuscular training planned to improve knee control.²⁶ In previous studies, poor frontal plane knee control has been associated with reduced hip muscle strength.^{25 27} Hip abduction strength and hip external rotation strength, in particular, are valuable predictors of frontal plane knee control.^{25 27 28} Crossley *et al* demonstrated that for every 1% improvement in hip abduction strength normalised to body weight, the FPKPA would improve by 0.2°.¹⁴ In addition, knee valgus can be a consequence of delayed activity or a lack of coactivation.^{14 15} Delayed gluteus medius activation was measured in subjects who performed poorly in the SLS compared with those who performed well.¹⁴ Mauntel *et al* suggested that knee valgus motion is an issue of muscular coactivation.¹⁵ They reported that subjects displaying valgus motion during the SLS had smaller coactivation ratios of the gluteus medius to hip

Table 2 ORs for potential ankle injury risk factors

Univariate analysis	OR	95% CI	P value
Categorical variables			
Basketball	1		
Floorball	0.72	0.39 to 1.34	0.29
Female	1		
Male	0.84	0.45 to 1.55	0.58
Age, intermediate (mean±SD)	1		
Age, low (<1 SD below mean,<13.9 years)	1.08	0.45 to 2.56	0.87
Age, high (>1 SD above mean,>17.5 years)	0.92	0.37 to 2.29	0.85
Height, intermediate (mean±SD)	1		
Height, low (<1 SD below mean,<164.2 cm)	1.03	0.46 to 2.26	0.95
Height, high (>1 SD above mean,>182.4 cm)	0.91	0.38 to 2.16	0.83
Weight, intermediate (mean±SD)	1		
Weight, low (<1 SD below mean,<54.7 kg)	0.82	0.31 to 2.20	0.70
Weight, high (>1 SD above mean,>74.6 kg)	0.94	0.40 to 2.23	0.89
BMI, intermediate (mean±SD)	1		
BMI, low (<1 SD below mean,<19.0)	0.80	0.32 to 1.98	0.63
BMI, high (>1 SD above mean,>23.9)	0.93	0.39 to 2.21	0.87
FPKPA, intermediate (mean±SD)	1		
FPKPA, low (<1 SD below mean,<2.7°)	1.18	0.46 to 2.98	0.73
FPKPA, high (>1 SD above mean,>23.8°)	2.37	1.13 to 4.98	0.02*
Training exposure, intermediate (mean±SD)	1		
Training exposure, low (<1 SD below mean,<162.4 hours)	1.14	0.50 to 2.60	0.76
Training exposure, high (>1 SD above mean,>346.0 hours)	0.71	0.25 to 2.03	0.52
Match exposure, intermediate (mean±SD)	1		
Match exposure, low (<1 SD below mean,<3.9 hours)	0.57	0.20 to 1.62	0.29
Match exposure, high (>1 SD above mean,>15 hours)	0.80	0.34 to 1.88	0.61

Continued

Table 2 Continued

Univariate analysis	OR	95% CI	P value
Match and training exposure, intermediate (mean±SD)	1		
Match and training exposure, low (<1 SD below mean,<169.6 hours)	1.02	0.43 to 2.42	0.96
Match and training exposure, high (>1 SD above mean,>357.7 hours)	0.84	0.31 to 2.23	0.72
Continuous variables			
Age (years)	1.00	0.84 to 1.20	0.97
Height (cm)	0.99	0.96 to 1.03	0.65
Weight (kg)	0.99	0.96 to 1.03	0.65
BMI (kg/m ²)	0.99	0.87 to 1.12	0.85
FPKPA (°)	1.02	0.99 to 1.05	0.24
Training exposure (hour)	1.00	1.00 to 1.00	0.87
Match exposure (hour)	1.01	0.96 to 1.06	0.79
Match and training exposure (hour)	1.00	1.00 to 1.00	0.86

Since only one variable achieved $P<0.20$ were identified in the univariate analysis, no multivariate analysis was performed.

* $P<0.05$.

BMI, body mass index; FPKPA, frontal plane knee projection angle.

adductor and the gluteus maximus to hip adductor, suggesting that subjects displaying knee valgus used a hip adductor-dominant strategy. These neuromuscular factors contributing to frontal plane knee control can be targeted with training.

Since previous research indicates that athletes are able to improve their knee control through training, neuromuscular training programmes should be used to improve knee control.^{26 29–34} Previously, the effects of neuromuscular training have been measured using the vertical drop jump test.³⁴ Using the visual assessment of frontal plane knee control, the SLS and vertical drop jump identified different subjects and approximately 20% of the subjects displaying reduced knee control would not have been identified using only one of the two tests.¹⁷ The SLS test could be used in addition to the vertical drop jump test to quantify the effects of neuromuscular training. However, this should be studied in future research.

Several studies have shown that the incidence of lower extremity injuries among adolescent athletes can be reduced by neuromuscular injury prevention programmes.^{35–45} In a recent meta-analysis, Hübscher *et al* reported that multi-intervention training programmes reduced the risk of lower extremity injuries by 39%, the risk of acute knee injuries by 54% and the risk of ankle sprains by 50%.³⁸ However, lack of intervention programme uptake in sports is a concern.³⁶ Currently, little is known about how much of the reduction in injury

Table 3 ORs for potential knee injury risk factors

Univariate analysis	OR	95% CI	P value
Categorical variables			
Basketball	1		
Floorball	1.53	0.69 to 3.41	0.30
Female	1		
Male	0.69	0.31 to 1.52	0.36
Age, intermediate (mean±SD)	1		
Age, low (<1 SD below mean,<13.9 years)	1.36	0.43 to 4.26	0.60
Age, high (>1 SD above mean,>17.5 years)	2.22	0.89 to 5.53	0.09*
Height, intermediate (mean±SD)	1		
Height, low (<1 SD below mean,<164.2 cm)	1.17	0.42 to 3.28	0.76
Height, high (>1 SD above mean,>182.4 cm)	0.81	0.27 to 2.50	0.72
Weight, intermediate (mean±SD)	1		
Weight, low (<1 SD below mean,<54.7 kg)	0.88	0.26 to 3.03	0.85
Weight, high (>1 SD above mean,>74.6 kg)	0.77	0.25 to 2.31	0.64
BMI, intermediate (mean±SD)	1		
BMI, low (<1 SD below mean,<19.0)	0.92	0.27 to 3.09	0.89
BMI, high (>1 SD above mean,>23.9)	1.14	0.42 to 3.12	0.80
FPKPA, intermediate (mean±SD)	1		
FPKPA, low (<1 SD below mean,<2.7°)	0.76	0.20 to 2.82	0.68
FPKPA, high (>1 SD above mean,>23.8°)	1.49	0.56 to 3.98	0.42
Training exposure, intermediate (mean±SD)	1		
Training exposure, low (<1 SD below mean,<162.4 hours)	1.43	0.54 to 3.77	0.48
Training exposure, high (>1 SD above mean,>346.0 hours)	0.58	0.13 to 2.72	0.49
Match exposure, intermediate (mean±SD)	1		
Match exposure, low (<1 SD below mean,<3.9 hours)	1.12	0.36 to 3.49	0.84
Match exposure, high (>1 SD above mean,>15 hours)	0.82	0.27 to 2.57	0.74

Continued

Table 3 Continued

Univariate analysis	OR	95% CI	P value
Match and training exposure, intermediate (mean±SD)	1		
Match and training exposure, low (<1 SD below mean,<169.6 hours)	1.22	0.44 to 3.42	0.70
Match and training exposure, high (>1 SD above mean,>357.7 hours)	0.57	0.12 to 2.63	0.47
Continuous variables			
Age (years)	1.12	0.90 to 1.39	0.32
Height (cm)	0.99	0.95 to 1.04	0.81
Weight (kg)	1.00	0.96 to 1.04	0.98
BMI (kg/m ²)	1.02	0.87 to 1.19	0.79
FPKPA (°)	1.01	0.97 to 1.05	0.59
Training exposure (hour)	1.00	0.99 to 1.00	0.35
Match exposure (hour)	1.01	0.94 to 1.08	0.86
Match and training exposure (hour)	1.00	0.99 to 1.00	0.36

*Only one variable achieved P<0.20; therefore, no multivariate analysis was performed.

BMI, body mass index; FPKPA, frontal plane knee projection angle.

risk is a result of improved knee control. It would be worthwhile to assess this by a randomised controlled trial with pretraining/post-training knee control measurements.

Ankle injury risk factors

Large FPKPA was associated with the risk of ankle injuries. It is known that ankle function contributes to knee valgus movement, but knee valgus has not previously been linked to ankle injuries. Mauntel *et al* found that subjects displaying valgus during the SLS had a limited dorsiflexion range of motion.¹⁵ They proposed that during the SLS, the limited dorsiflexion range of motion causes neuromuscular compensation, which is observed as hip adduction. However, this is not supported by the findings of Zeller *et al*.¹⁸ They compared the kinematics of men and women during the SLS and detected significantly more knee valgus, ankle dorsiflexion and ankle pronation in women.¹⁸ Our results indicate an association between frontal plane knee control and the risk of ankle injuries, but our data do not provide further insight to the role of ankle function on knee valgus.

SLS test as a screening tool

The ROC curve analyses indicate that the 2D analysis of the SLS test is not a suitable screening tool for lower extremity injuries or ankle injuries due to poor combined specificity and sensitivity. Bahr suggested that the main challenge with athletic screening tests is the overlap between the groups of injured and uninjured athletes.⁴⁶

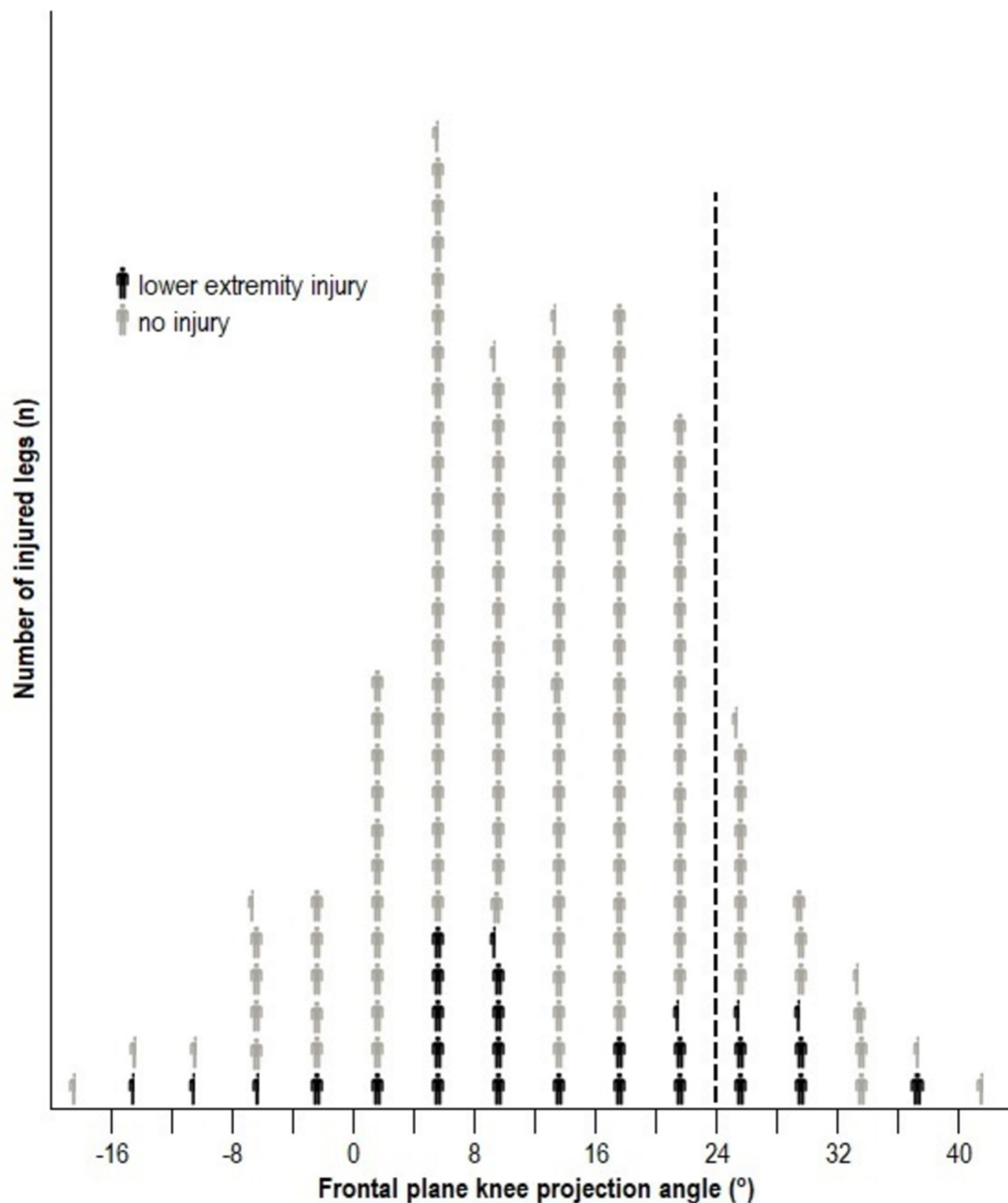


Figure 3 Representation of the distribution of injured and uninjured lower extremities by frontal plane knee projection angle. Each full icon represents two lower extremities, not necessary of the same athlete. The vertical line represents the cut-off point for the high frontal plane knee projection angle ($>23.8^\circ$).

Bahr's conclusion is supported by our data, as illustrated in [figure 3](#). The FPKPA fails to divide the athletes into two distinctive groups, which would be necessary for a screening tool. Our results demonstrate the SLS alone is not specific and sensitive enough to be used as a screening tool.

Study strengths and weaknesses

The size of the cohort can be viewed as a strength of the study: complete data were obtained from 306 athletes. In addition, the prospective nature of the injury collection and careful video assessment of the SLS test by a single researcher were study strengths.

However, our study has also some limitations. The purpose of this study was to analyse the predictive value of the FPKPA on future injuries, and therefore the analysis

was performed on athletes who had been free from injury for 12 months prior to the study. Previous injuries were collected using a questionnaire with a 12-month recall period; therefore, recall bias could have influenced the prevalence of previous injuries. Additionally, the information on injured athletes was collected from the coaches. It is possible that the coaches were not aware of all minor injuries and this could have led to under-reporting. For this reason, we excluded all injuries that did not result in time-loss from the analyses.

During the study, 55 athletes did not complete the 12-month follow-up, making the drop-out rate 15%. In most cases, the subject quit the sport. The decline in physical activity during adolescence is well documented.⁴⁷

Therefore, we consider the drop-out rate in this study to be typical of the population.

CONCLUSIONS

This study provides further understanding of the role of knee control on injury risk. The findings demonstrate that a large FPKPA during the SLS test is associated with an elevated risk of lower extremity injuries. However, the results indicate that the FPKPA measured during the SLS test is not by itself a sufficient screening tool for the risk of future injuries.

Acknowledgements We would like to thank the athletes, coaches and contact persons of each participating team for their excellent cooperation. We are grateful to physiotherapist Irja Lahtinen for coordinating and conducting the baseline testing and to statistician Kari Tokola for his statistical advice.

Contributors All authors were involved in conceiving the study. All authors contributed to study concept and design. KP and AMR were responsible for conducting the data acquisition. AMR was responsible for the video analysis, data analysis and interpretation. AMR was the significant manuscript writer. KP, TK, TV, PK, AH, UMK, JA, JPe and JPa were significant manuscript revisers. All authors have approved the submitted version of the manuscript. AMR is the guarantor.

Funding This study was financially supported by the Finnish Ministry of Education and Culture, the Competitive State Research Financing of the Expert Responsibility Area of Tampere University Hospital (Grants 9N053, 9S047, 9T046), and the Foundation of Sports Institute (Urheiluoipistosäätiö).

Competing interests None declared.

Patient consent Obtained.

Ethics approval The study was approved by the Ethics Committee of Pirkanmaa Hospital District (ETL code R10169).

Provenance and peer review Not commissioned; externally peer reviewed.

Open Access This is an Open Access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: <http://creativecommons.org/licenses/by-nc/4.0/>

© Article author(s) (or their employer(s) unless otherwise stated in the text of the article) 2018. All rights reserved. No commercial use is permitted unless otherwise expressly granted.

REFERENCES

- Agel J, Olson DE, Dick R, *et al.* Descriptive epidemiology of collegiate women's basketball injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *J Athl Train* 2007;42:202-10.
- Clausen MB, Zebis MK, Möller M, *et al.* High injury incidence in adolescent female soccer. *Am J Sports Med* 2014;42:2487-94.
- Møller M, Attermann J, Myklebust G, *et al.* Injury risk in Danish youth and senior elite handball using a new SMS text messages approach. *Br J Sports Med* 2012;46:531-7.
- Pasanen K, Parkkari J, Kannus P, *et al.* Injury risk in female floorball: a prospective one-season follow-up. *Scand J Med Sci Sports* 2008;18:49-54.
- Söderman K, Adolphson J, Lorentzon R, *et al.* Injuries in adolescent female players in European football: a prospective study over one outdoor soccer season. *Scand J Med Sci Sports* 2001;11:299-304.
- Åman M, Forsblad M, Henriksson-Larsén K. Incidence and severity of reported acute sports injuries in 35 sports using insurance registry data. *Scand J Med Sci Sports* 2016;26:451-62.
- Le Gall F, Carling C, Reilly T. Injuries in young elite female soccer players: an 8-season prospective study. *Am J Sports Med* 2008;36:276-84.
- Myer GD, Ford KR, Hewett TE. Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *J Athl Train* 2004;39:352-64.
- Read PJ, Oliver JL, De Ste Croix MB, *et al.* Neuromuscular risk factors for knee and ankle ligament injuries in male youth soccer players. *Sports Med* 2016;46:1059-66.
- 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;33:492-501.
- Krosshaug T, Steffen K, Kristianslund E, *et al.* The vertical drop jump is a poor screening test for ACL injuries in female elite soccer and handball players: a prospective cohort study of 710 athletes. *Am J Sports Med* 2016;44:874-83.
- Leppänen M, Pasanen K, Kujala UM, *et al.* Stiff landings are associated with increased ACL injury risk in young female basketball and floorball players. *Am J Sports Med* 2017;45:386-93.
- O'Kane JW, Tencer A, Neradilek M, *et al.* Is knee separation during a drop jump associated with lower extremity injury in adolescent female soccer players? *Am J Sports Med* 2016;44:318-23.
- Crossley KM, Zhang WJ, Schache AG, *et al.* Performance on the single-leg squat task indicates hip abductor muscle function. *Am J Sports Med* 2011;39:866-73.
- Mauntel TC, Begalle RL, Cram TR, *et al.* The effects of lower extremity muscle activation and passive range of motion on single leg squat performance. *J Strength Cond Res* 2013;27:1813-23.
- Mauntel TC, Frank BS, Begalle RL, *et al.* Kinematic differences between those with and without medial knee displacement during a single-leg squat. *J Appl Biomech* 2014;30:707-12.
- Stensrud S, Myklebust G, Kristianslund E, *et al.* Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. *Br J Sports Med* 2011;45:589-95.
- Zeller BL, McCrory JL, Kibler WB, *et al.* Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med* 2003;31:449-56.
- McLean SG, Walker K, Ford KR, *et al.* Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *Br J Sports Med* 2005;39:355-62.
- Munro A, Herrington L, Carolan M. Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. *J Sport Rehabil* 2012;21:7-11.
- Pasanen K, Rossi MT, Parkkari J, *et al.* Predictors of lower extremity injuries in team sports (PROFITS-study): a study protocol. *BMJ Open Sport Exerc Med* 2015;1:e000076.
- Räisänen A, Pasanen K, Krosshaug T, *et al.* Single-leg squat as a tool to evaluate young athletes' frontal plane knee control. *Clin J Sports Med* 2016;26:478-82.
- Bahr R, Holme I. Risk factors for sports injuries-a methodological approach. *Br J Sports Med* 2003;37:384-92.
- Hosmer DW, Lemeshow S, Sturdivant RX. *Applied logistic regression*. 3rd Edn Electronic book: John Wiley & Sons, Incorporated, 2013:177.
- Willson JD, Ireland ML, Davis I. Core strength and lower extremity alignment during single leg squats. *Med Sci Sports Exerc* 2006;38:945-52.
- Myer GD, Ford KR, Brent JL, *et al.* Differential neuromuscular training effects on ACL injury risk factors in 'high-risk' versus 'low-risk' athletes. *BMC Musculoskelet Disord* 2007;8:39.
- Claiborne TL, Armstrong CW, Gandhi V, *et al.* Relationship between hip and knee strength and knee valgus during a single leg squat. *J Appl Biomech* 2006;22:41-50.
- Stickler L, Finley M, Gulgin H. Relationship between hip and core strength and frontal plane alignment during a single leg squat. *Phys Ther Sport* 2015;16:66-71.
- Chappell JD, Limpisvasti O. Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *Am J Sports Med* 2008;36:1081-6.
- Kato S, Urabe Y, Kawamura K. Alignment control exercise changes lower extremity movement during stop movements in female basketball players. *Knee* 2008;15:299-304.
- Lim BO, Lee YS, Kim JG, *et al.* Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. *Am J Sports Med* 2009;37:1728-34.
- Myer GD, Ford KR, McLean SG, *et al.* The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *Am J Sports Med* 2006;34:445-55.
- Myer GD, Ford KR, Palumbo JP, *et al.* Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res* 2005;19:51-60.
- Noyes FR, Barber-Westin SD, Fleckenstein C, *et al.* The drop-jump screening test: difference in lower limb control by gender and effect

- of neuromuscular training in female athletes. *Am J Sports Med* 2005;33:197–207.
35. Emery CA, Meeuwisse WH. The effectiveness of a neuromuscular prevention strategy to reduce injuries in youth soccer: a cluster-randomised controlled trial. *Br J Sports Med* 2010;44:555–62.
 36. Emery CA, Roy TO, Whittaker JL, *et al.* Neuromuscular training injury prevention strategies in youth sport: a systematic review and meta-analysis. *Br J Sports Med* 2015;49:865–70.
 37. Hewett TE, Lindenfeld TN, Riccobene JV, *et al.* The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med* 1999;27:699–706.
 38. Hübscher M, Zech A, Pfeiffer K, *et al.* Neuromuscular training for sports injury prevention: a systematic review. *Med Sci Sport Exerc* 2010;42:413–21.
 39. Häggglund M, Atroshi I, Wagner P, *et al.* Superior compliance with a neuromuscular training programme is associated with fewer ACL injuries and fewer acute knee injuries in female adolescent football players: secondary analysis of an RCT. *Br J Sports Med* 2013;47:974–9.
 40. Junge A, Rösch D, Peterson L, *et al.* Prevention of soccer injuries: a prospective intervention study in youth amateur players. *Am J Sports Med* 2002;30:652–9.
 41. Longo UG, Loppini M, Berton A, *et al.* The FIFA 11+ program is effective in preventing injuries in elite male basketball players: a cluster randomized controlled trial. *Am J Sports Med* 2012;40:996–1005.
 42. Mandelbaum BR, Silvers HJ, Watanabe DS, *et al.* Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med* 2005;33:1003–10.
 43. Marshall DA, Lopatina E, Lacny S, *et al.* Economic impact study: neuromuscular training reduces the burden of injuries and costs compared to standard warm-up in youth soccer. *Br J Sports Med* 2016;50:1388–93.
 44. Olsen OE, Myklebust G, Engebretsen L, *et al.* Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *BMJ* 2005;330:449.
 45. Rössler R, Donath L, Verhagen E, *et al.* Exercise-based injury prevention in child and adolescent sport: a systematic review and meta-analysis. *Sports Med* 2014;44:1733–48.
 46. Bahr R. Why screening tests to predict injury do not work- and probably never will...: a critical review.. *Br J Sports Med* 2016;bjsports - 2016-096256.
 47. Dumith SC, Gigante DP, Domingues MR, *et al.* Physical activity change during adolescence: a systematic review and a pooled analysis. *Int J Epidemiol* 2011;40:685–98.



Association between frontal plane knee control and lower extremity injuries: a prospective study on young team sport athletes

Anu M Räisänen, Kati Pasanen, Tron Krosshaug, Tommi Vasankari, Pekka Kannus, Ari Heinonen, Urho M Kujala, Janne Avela, Jarmo Perttunen and Jari Parkkari

BMJ Open Sport Exerc Med 2018 4:
doi: 10.1136/bmjsem-2017-000311

Updated information and services can be found at:
<http://bmjopensem.bmj.com/content/4/1/e000311>

These include:

References

This article cites 45 articles, 10 of which you can access for free at:
<http://bmjopensem.bmj.com/content/4/1/e000311#ref-list-1>

Open Access

This is an Open Access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited and the use is non-commercial. See: <http://creativecommons.org/licenses/by-nc/4.0/>

Email alerting service

Receive free email alerts when new articles cite this article. Sign up in the box at the top right corner of the online article.

Notes

To request permissions go to:
<http://group.bmj.com/group/rights-licensing/permissions>

To order reprints go to:
<http://journals.bmj.com/cgi/reprintform>

To subscribe to BMJ go to:
<http://group.bmj.com/subscribe/>

IV

Investigation of knee control as a lower extremity injury risk factor: A prospective study in youth football

by

Räsänen A, Arkkila H, Vasankari T, Steffen K, Parkkari J, Kannus P, Forsmann H,
Pasanen K

Scandinavian Journal of Medicine & Science in Sports. In press.

Reproduced with kind permission by John Wiley and Sons, Inc.

Copyright and Copying

Copyright © 2018 John Wiley & Sons A/S. Published by John Wiley & Sons Ltd. All rights reserved. No part of this publication may be reproduced, stored or transmitted in any form or by any means without the prior permission in writing from the copyright holder. Authorization to copy items for internal and personal use is granted by the copyright holder for libraries and other users registered with their local Reproduction Rights Organisation (RRO), e.g. Copyright Clearance Center (CCC), 222 Rosewood Drive, Danvers, MA 01923, USA (www.copyright.com), provided the appropriate fee is paid directly to the RRO. This consent does not extend to other kinds of copying such as copying for general distribution, for advertising or promotional purposes, for creating new collective works or for resale. Special requests should be addressed to permissionsuk@wiley.com

Investigation of knee control as a lower extremity injury risk factor: A prospective study in youth football

MHSc Anu M Räisänen¹, BM Hillevi Arkkila², MD Tommi Vasankari³, PhD Kathrin Steffen⁴, MD Jari Parkkari¹, MD Pekka Kannus³, PhD Hannele Forsman⁵, PhD Kati Pasanen^{1,6}

- 1) Tampere Research Center of Sports Medicine, UKK Institute for Health Promotion Research, Tampere, Finland
- 2) Faculty of Medicine and Life Sciences, University of Tampere, Tampere, Finland
- 3) UKK Institute for Health Promotion Research, Tampere, Finland
- 4) Oslo Sports Trauma Research Center, Norwegian School of Sports Sciences, Oslo, Norway
- 5) Eerikkilä Sports Institute Training Center, Tammela, Finland
- 6) Sport Injury Prevention Research Centre, Faculty of Kinesiology, University of Calgary, Calgary, Alberta, Canada

Corresponding author:

Anu M. Räisänen

Tampere Research Centre of Sports Medicine, UKK Institute for Health Promotion Research

PO BOX 30, 33501 Tampere, Finland

Tel: +358 40 723 4471

Fax: +358 3 282 9200

E-mail: anu.raisanen@uta.fi

Twitter: @araisanen

ABSTRACT

This prospective study in youth football examined the relationship between frontal plane knee projection angle (FPKPA) during the single-leg squat and sustaining an acute lower extremity injury or acute non-contact lower extremity injury. Secondly, side-to-side asymmetry in FPKPA and sex as injury risk factors were explored. In addition, we investigated the influence of age, sex and leg dominance on the FPKPA. A total of 558 youth football players (U11 to U14), participated in the single-leg squat and prospective injury registration. FPKPA was not found as a risk factor for injuries at this age. There was no difference in the mean FPKPA between sexes. However, FPKPA was associated with age; oldest subjects displayed the smallest FPKPA. Among boys, the frontal plane knee control improved by age. Among girls, the relationship between age and FPKPA was not as clear but the oldest girls displayed the smallest mean FPKPA in the study ($12.2^{\circ} \pm 8.3^{\circ}$). The FPKPA was greater on the dominant kicking leg compared to the non-dominant support leg ($P < 0.001$ for boys, $P = 0.001$ for girls). However, side-to-side asymmetry in FPKPA was not associated with future injuries. In conclusion, frontal plane knee control in the single-leg squat was not associated with lower extremity injuries among young football players.

KEYWORDS

athletic injuries, leg injuries, risk factors, risk assessment, soccer, youth sports

INTRODUCTION

With football (soccer) being the most popular sport in the world, football injuries have been an interest of sports medicine research for several decades.^{1,2} Among the young football players under the age of 14 years, the knowledge of potentially modifiable lower extremity injury risk factors is still limited.

Sports participation is a major cause of injuries among youth.³ In addition to short term consequences of sports injuries, it is important to address the long-term outcomes. Sports injuries, especially knee injuries, can lead to higher likelihood of overweight or obesity and reduced knee function⁴, and higher risk of osteoarthritis later in life.⁵ Acute lower extremity injuries are the most common injuries in youth football, with ankle, knee and thigh being the most frequently injured body parts.² Among children, football is a safe sport and injuries are rarely serious.⁶ However, in academy youth football (ages 9 to 19 years), each injury, on average, stopped the player from participating in normal activities for 21.9 days.⁷ The youth players miss about 6% of their development time through injuries.⁷ There is a clear need to prevent injuries during the valuable developmental years. Neuromuscular control is modifiable through training⁸ and neuromuscular training has been shown to improve knee control^{9,10} and reduce injuries.¹¹⁻¹³

The single-leg squat (SLS) is commonly used in clinical practice to identify reduced frontal plane knee control, which can manifest as knee valgus. Knee valgus can be harmful, since it alters the loads experienced by different tissues in the lower extremities. If the ability to control trunk, hip and knee motions during athletic tasks is poor, the athlete can allow the ground reaction forces to control the lower extremity alignment.¹⁴ This may lead to high loads on the knee ligaments and could be a mechanism contributing to lower extremity injuries.¹⁵ In addition to strength and neuromuscular activation of hip and trunk muscles, ankle function can also contribute to frontal plane knee motions. If ankle dorsiflexion is limited, for example due to decreased extensibility of the

gastrocnemius/soleus complex, athlete might try to compensate for this by moving their knee medially towards valgus during athletic tasks.^{16,17}

The two-dimensional (2D) video analysis method of the SLS is a valid¹⁸ and reliable^{19,20} tool for measuring frontal plane knee control. Previous studies have associated greater frontal plane knee projection angle (FPKPA) during the SLS with reduced hip abduction strength.^{21–23} For every 1% improvement in hip abduction strength normalized to body weight, the FPKPA would improve by 0.2°. ²² The reduced hip abduction strength interacting with increased range of passive hip internal rotation contributes to a greater FPKPA.²⁴ Individuals with poor frontal plane control use a hip adductor dominant strategy during the SLS.²⁵ Other strength measurements associated with frontal plane knee control are knee flexion and knee extension²¹, trunk side flexion²⁶ and hip external rotation.²⁷ A recent study on children and adolescents found no differences between boys and girls in the SLS performance scores based on visual assessment.²⁸ In our previous study, greater FPKPA during the SLS was associated with a higher risk of acute non-contact lower extremity injury and acute non-contact ankle injury in young (mean age 15.7 years) team sport athletes²⁹ but there are no previous studies on this topic in subjects under the age of 14 years.

The specific objective of this study was to investigate the association between FPKPA during the SLS and acute contact and non-contact lower extremity injuries in youth football players. The secondary aim was to investigate if sex or side-to-side asymmetry of FPKPA is associated with acute lower extremity or acute non-contact lower extremity injury. In addition, we set out to study the effects of age, sex and leg dominance on FPKPA.

METHODS

Study design and participants

This study is part of a cluster-randomized controlled trial on sports injury prevention in youth football (RCT ISRCTN14046021). The cohort in the present study consists of the control group of this RCT (n=737). Players who did not participate in the baseline SLS (n=163) or the injury registration (n=6) were excluded. In addition, the players who dropped out during the follow-up (n=10) were excluded from the current study since equal length of follow-up was necessary for the analysis. Numbers of subjects in each stage of the study are presented in Figure 1. The study was carried out in collaboration with Sami Hyypiä Academy, the training and research centre of Finnish football. Every second year, the Sami Hyypiä Academy selects about 20 youth clubs to participate in the player development monitoring system in which the talented U11 to U14 boys and girls participate on a three-day player development monitoring event twice a year. Every player who was an official member of the participating team and had no major injury at baseline was eligible to enter the study. All players and their parent/legal guardian provided written informed consent. The study was approved by the Ethics Committee of Pirkanmaa Hospital District (ETL-code R13110).

Baseline measurements

During their team's player development monitoring event in the fall 2014 (end of September to the beginning of December), the subjects participated in the SLS and height and weight measurements. From height and weight, body mass index (BMI, kg/m^2) was calculated. Each subject completed a baseline questionnaire, which included questions about the subject's age, sex, years of playing football, dominant leg, family history of musculoskeletal disorders, chronic illnesses, orthopaedic surgeries, menstrual cycle and previous injuries. The players were categorised into age groups of under 11 years (U11), under 12 years (U12), under 13 years (U13) and under 14 years (U14) by their age at the baseline test. The 18 players, who had not yet turned 10 years, were included in U11.

The test protocol for the SLS and the 2D video analysis method is based on the work of Stensrud et al.²⁰ and has been described in detail previously.³⁰ An alteration to the previous protocol was made by cutting out the warm-up. The warm-up was not considered necessary since in the present study the SLS test was not followed by the vertical drop jump test, as had been the case in previous studies.^{20,31} First, square pieces of sports tape were attached to the left and right anterior superior iliac spine and tuberositas tibiae. Secondly, to standardize the knee flexion, the player performed a two-leg squat to 90° knee flexion, measured with a plastic goniometer (Baseline, USA). At 90° knee flexion, a string with a metal object at the distal end was attached to the lateral side of the thigh. The string was adjusted to the length in which the metal object would slightly touch the ground. This was repeated on the other leg. When the player performed the SLS on a metal plate, they could hear the metal object touching the plate when they reached the 90° knee flexion. Each player was allowed one practise attempt before they performed three SLSs to 90° knee flexion on right leg and repeated the procedure on left leg. The players were instructed to hold their hands at their waist and keep their eyes focused straight ahead during the trial. To capture the 2D frontal plane knee joint kinematics, the trials were recorded by a high definition video camera (Panasonic HDC-SD9C, Panasonic, Japan) positioned 4.5 m in front of the metal plate.

The 2D video analysis was performed by the primary investigator (A.M.R) using a Java-based computer software (ImageJ, National Institutes of Health). In the 2D video analysis, the FPKPA was measured from each valid squat. The squat was deemed invalid if the non-weight-bearing leg was held in the front or to the side or it touched the floor or if the player fell, looked down or moved their hands from the waist. The mean FPKPA for the right and the left leg were calculated and a minimum of two valid squats per leg were required. The FPKPA was calculated as the intersection of a line created by the anterior superior iliac spine and knee joint centre and the line created by the knee joint centre and the ankle joint centre. Neutral alignment was considered 0°, positive values

represented valgus alignment, and negative values represented varus alignment. The measurement of FPKPA is presented in Figure 2. In addition to mean FPKPA, side-to-side difference in the mean FPKPA between the two lower extremities was calculated (FPKPA asymmetry).

Injury definition and injury registration

Injury registration was carried out by text messaging. The follow-up period lasted for 20 weeks, from January to June. After each follow-up week, the player's parent/legal guardian received a text message regarding new injuries: "Has your child had any musculoskeletal complaint or injuries during the previous seven days (yes/no)." After each complaint or injury, the study physiotherapists contacted the injured player and/or their parent/legal guardian and collected details of the injury by standardized phone interview.

An injury was defined according to Fuller et al.³² *'any physical complaint sustained by a player that result from football training or playing, causing a need for medical attention or time loss from fully football activities.'* The player was defined as injured until he/she was able to train and play normally again. The present study focused on the acute lower extremity (hip/groin/thigh/knee/shin/calf/ankle/foot) injuries. Non-contact injuries were defined as injuries that resulted without direct contact to the injured body part.

Statistical methods

To consider the possibly non-linear relationship between intrinsic factors and the risk of injury³³, categorical variables were formed based on the continuous variables utilizing the cohort mean and standard deviation (SD). Age, height, weight, FPKPA, and FPKPA asymmetry were categorised as above normal (+1 SD above the mean), normal (within 1 SD of the mean), and below normal (-1 SD below the mean) of the mean value for that risk factor in the cohort. For the subgroup analyses

by sex, the categorised variables were calculated based on the mean values of each subgroup. BMI was categorised as healthy, low and overweight based on the cut-off values for adolescents.^{34,35}

The statistical analyses were performed using SPSS (v 24, SPSS Inc., Chicago, Illinois, USA). To compare injured and uninjured subjects, the Mann–Whitney *U* test was used to test the variables that were not normally distributed (age, height, weight, BMI), the independent samples *t* test was used for the normally distributed variables (right FPKPA, left FPKPA), and the χ^2 test was used for the categorical variables (sex). The independent samples *t* test was used to investigate the differences in mean FPKPA between sexes. To analyse the differences in mean FPKPA between right and left leg and dominant and non-dominant leg, the paired samples *t* test was used. One-way ANOVA was used to investigate the differences in the FPKPA between age groups. The significance level was set at $P < 0.05$.

A generalized linear mixed model for binary data with injury/no injury as the dependent variable was used to analyse the potential risk factors. The analyses were performed using each leg as a unit of analysis. Team and leg were used as random effects. First, the intrinsic factors were analysed using the univariate model. All the variables with a *P*-value < 0.20 in the univariate analysis were entered into a multivariate model. If both the categorical and the continuous version of the same variable achieved $P < 0.20$, the variable with a smaller *P*-value was entered into the multivariate model. In the multivariate analysis, the significance level was set at $P < 0.05$.

RESULTS

A total of 558 players participated in the baseline SLS and completed the injury surveillance. Out of the 558 players, 445 were boys and 113 girls. Player characteristics by sex and age group are presented in Table 1. Dominant leg (preferred leg for kicking the ball), was right for 88% and left

for 12% of the players. Two players did not name a preferred leg. During the follow-up, 285 acute lower extremity injuries were reported, out of which 142 (50%) were non-contact injuries. Out of the 558 players, 37% (n=205) were injured at least once. The majority of the injuries (41%) were minor (1 to 3 days of absence), however, moderate injuries (8 to 28 days of absence) were also common (25%) (Figure 3). The ankle was the most commonly injured body part (32% of all injuries), followed by the knee (20%) (Figure 4). The dominant leg was injured in 51% and non-dominant leg in 48% of the cases. In three slight injuries, the player was unable to report which leg was injured and these players were removed from the risk factor analysis. Number of injured legs by sex and age group are presented in Figure 5. A total of 40 players were unable to perform enough valid trials on either leg and 92 players only performed enough valid trials on one leg. When comparing the injured athletes to the uninjured, there were no differences in the mean values of age, height, weight, BMI, number of years playing football or the proportion of boys and girls.

Risk factors for acute lower extremity injuries

In the univariate analysis for the risk of a new acute lower extremity injury, the categorical weight and BMI and continuous height, weight and BMI achieved $P < 0.20$ (Table 2). Continuous height and weight and categorical BMI were entered into the multivariate model based on the smaller P -value. In the multivariate analysis there were no associations between the variables and the risk of lower extremity injuries (Table 3).

In the subgroup analysis of boys, categorical height and weight and continuous height, weight and age achieved $P < 0.20$. Categorical height and weight and continuous age were entered in to the multivariate analysis but were not associated with acute lower extremity injury (Table 3). Among girls, none of the variables achieved $P < 0.20$ in the univariate analysis, therefore no multivariate

analysis was performed. The univariate analyses for lower extremity injury for boys and girls are presented in supplementary material (Appendix tables 1–2).

Risk factors for acute non-contact lower extremity injuries

In the univariate analysis of new acute non-contact lower extremity injury risk in the entire cohort, low BMI and high FPKPA asymmetry achieved $P<0.20$ in the univariate analysis (Table 4). In the multivariate analysis, the analysed factors were not associated with non-contact injuries (Table 5).

For boys, low BMI and high FPKPA asymmetry were entered into the multivariate model but were not associated with non-contact injury (Table 5). For girls, categorised weight and ability to perform valid SLS test were entered into the multivariate model but were not associated with non-contact lower extremity injury (Table 5). Univariate analyses for a new non-contact lower extremity injury by sex are presented in supplementary material (Appendix tables 3–4).

Effects of age, sex and leg dominance on FPKPA

There was no difference in the mean FPKPA between boys and girls. There were significant differences in FPKPA between age groups among boys ($F=3.09$, $P=0.03$) and girls ($F=4.22$, $P=0.006$). Among boys, the FPKPA decreased as age increased. Among girls, the largest mean FPKPA was detected in the U12 age group. The oldest girls demonstrated best frontal plane knee control (mean FPKPA $12.2^\circ \pm 8.3^\circ$). The mean values for FPKPA by sex and age group for right, left, dominant and non-dominant leg are presented in Table 6.

There were significant differences in the mean FPKPA between the right and the left leg and the dominant and the non-dominant leg (Table 6). Among both sexes, the FPKPA was greater on the right leg compared to the left ($P<0.001$ for boys and for girls) and greater on the dominant compared to the non-dominant leg ($P<0.001$ for boys and $P=0.001$ for girls). When further analysed

by age group, the differences were statistically significant in all age groups among boys and U11 girls.

DISCUSSION

Our study on a cohort of youth football players investigated the relationship between FPKPA and sustaining an acute lower extremity injury and non-contact lower extremity injury. We found no association between the FPKPA and future injuries.

FPKPA and the risk of lower extremity injury

In the current study, we found no association between the FPKPA during the SLS and future lower extremity injuries. In our previous study among older team sport athletes (mean age 15.7 ± 1.8 years), we detected a significant association between FPKPA and acute lower extremity injury and acute ankle injury: displaying high FPKPA was associated with a higher odds of injury.²⁹ The association between frontal plane knee control and the risk of injuries has not been previously studied in young, under 14-year-old athletes. Padua et al.³⁶ utilised another field-assessment test, the Landing Error Scoring System, to study the association between high-risk movement patterns and the risk of anterior cruciate ligament injury. Out of the cohort of 11 to 17-year-old football players, 25% were U13 players. The athletes who were injured during the follow-up demonstrated more high-risk movement patterns during the test than the uninjured players. However, none of the injured players were under 13-years-old. Generally in sports, the under 13-year-olds have a lower risk of injury than older adolescents³⁷ and in youth football, overall injury incidence increases along with age.^{2,6,7,38} The lower risk of injury among the under 13-year-olds could be a possible explanation why no significant associations were detected between the analysed intrinsic factors and future injuries.

Leg dominance

Leg dominance is an imbalance in the strength and joint kinematics in the lower extremities¹⁵ and it has been associated with an increased risk of lower extremity injuries.^{39–41} We detected significantly greater FPKPA in the dominant leg, which suggests an imbalance in knee control between legs. However, displaying great FPKPA asymmetry was not associated with future injuries. Findings on the side-to-side differences must be interpreted with caution since the starting leg was not randomised. The SLS test was always performed on the right leg first, which was the dominant leg for most of the players. The learning effect could have influenced the results; it is possible that the SLS test was harder on the first attempts, which were done on the right leg. Therefore, the side-to-side asymmetry as a potential injury risk factor should be investigated further using randomisation of the starting leg.

Differences in FPKPA and injury risk between boys and girls

There was no difference in the mean FPKPA angle between boys and girls. This is in agreement with a prior study on adolescent SLS performance.²⁸ Agresta et al. (2016) evaluated frontal plane knee control during the SLS by visual assessment and detected no differences between sexes. In the current study, we detected differences in the FPKPA between age groups. Among boys, the frontal plane knee control improved along with age. Among girls, the relationship between age and FPKPA was not as clear. The oldest girls (U14) had the lowest mean FPKPA ($12.0^\circ \pm 8.1^\circ$) in the study. The highest FPKPA among girls was measured in the U12 group ($19.4^\circ \pm 11.2^\circ$). However, these findings on FPKPA may be somewhat limited by the small number of female subjects in this study; the girls' age groups consisted of 24 to 32 subjects.

Previous studies on youth football have reported no differences in injury risk between boys and girls.^{2,6,42,43} We analysed sex as a potential risk factor in the entire cohort but detected no significant associations. In addition, separate risk factor analyses were performed for boys and girls. However,

none of the analysed intrinsic factors were associated with injuries. Among the young football players, sex does not seem to affect lower extremity injury risk.

The single-leg squat test

The SLS test is used in clinical practice to assess frontal plane knee control. The visual assessment of frontal plane knee control correlates well with the FPKPA, when assessment is performed by experienced observer.³⁰ Previous studies on young athletes have shown that reduced frontal plane knee control is associated with higher risk of future injuries^{29,39,44,45}, although all the studies are not in agreement.⁴⁶ Since reduced knee control has been identified as an injury risk factor, using movement control tests to identify athletes who could reduce their injury risk by improving knee control seems sensible. In a previous study, different athletes were identified as having reduced knee control by the vertical drop jump and the SLS.²⁰ Therefore, it seems rational to use both, a jump-landing task and the SLS, to identify athletes with reduced knee control. When interpreting the results it must be kept in mind that sports injuries are multifactorial and movement control test results do not predict injuries but they do provide valuable information individual movement control and injury risk.

However, one factor to consider is the SLS test procedure. In the current study, the subjects were required to squat to 90° knee flexion. In some prior studies on SLS, the knee flexion angle has been determined at 60°^{21,23–26,28}, 90°^{20,29,30} or the subjects to squat as far as possible while maintaining balance.^{22,47} The procedure used here has been previously used among adults and older adolescents and it has been able to differentiate between the athletes.^{20,29,30} In the present study, 40 players were not able to perform valid SLS trials on either leg and additional 92 players only performed enough valid trials on one leg. It is possible that among these young athletes, this test procedure could be too demanding for part of the population. The double-legged squat might be a more suitable tool to

assess knee control among young athletes⁴⁸ and should be investigated further as potential, low level movement control test.

Strength and limitations

The weekly injury registration via text message was well received by the parents and the players and can be viewed as a strength of the study. The text messaging system made it possible for the players (or the parent) to report all musculoskeletal complaints. This can be considered more accurate than collecting injury data from coaches. The size of the cohort can be viewed as a strength of the current study. To our knowledge, this is the largest study describing SLS performance among adolescents and the first one to measure the FPKPA in the SLS in young subjects. However, the lack of exposure data can be viewed as a limitation since we are not able to analyse whether the players getting injured were exposed more or less than those not getting injured.

In the SLS protocol, the test was always performed on the right leg first. This can contribute to the significant differences detected between the right and left leg and dominant and non-dominant leg. This is considered a source of bias. We recommend randomising the starting leg in the SLS test procedure in future studies. In addition, the difficulty of the SLS test, as discussed previously, is a limitation to the study.

CONCLUSIONS

Frontal plane knee control is not associated with the risk of lower extremity injuries among young football players. There were significant side-to-side differences in frontal plane knee control between the dominant and non-dominant leg but displaying side-to-side asymmetry in FPKPA was not associated with future injuries.

PERSPECTIVES

Football is the most popular sport in the world. Young football players lose valuable training time due to injuries. There is a need to identify modifiable risk factors which are associated with a higher risk of lower extremity injuries. The results of this study indicate that among young football players, the single-leg squat test is not a suitable tool to assess the risk of future injuries.

ACKNOWLEDGEMENTS

The authors would like to thank the athletes and their parents and coaches of the participating teams for their excellent cooperation. We appreciate all the work the staff of Eerikkilä Sports Institute has done to make this study possible. We are grateful to all the study assistants for their work the baseline measurements and to the study physiotherapists for their work on the injury registration. We would also like to thank statistician Kari Tokola for providing statistical advice. This study was financially supported by the Finnish Ministry of Education and Culture, the Competitive State Research Financing of the Expert Responsibility Area of Tampere University Hospital (Grant 9S049, 9U044), the Foundation of Sports Institute (Urheiluoopistosäätiö) and the Scientific Council of City of Tampere (Tampereen kaupungin tiederahasto).

Conflicts of interest

The authors declare that they have no conflicts of interest relevant to the content of the study.

REFERENCES

1. Dvorak J, Junge A. Football injuries and physical symptoms. A review of the literature. *Am J Sports Med.* 2000;28(5):S3-S9. doi:10.1177/28.suppl_5.S-3.
2. Faude O, Rößler R, Junge A. Football injuries in children and adolescent players: are there clues for prevention? *Sport Med.* 2013;43(9):819-837.
3. Pickett W, Molcho M, Simpson K, et al. Cross national study of injury and social determinants in adolescents. *Inj Prev.* 2005;11(4):213-218. doi:10.1136/ip.2004.007021.
4. Whittaker JL, Woodhouse LJ, Nettel-Aguirre A, Emery CA. Outcomes associated with early post-traumatic osteoarthritis and other negative health consequences 3-10 years following knee joint injury in youth sport. *Osteoarthr Cartil.* 2015;23(7):1122-1129. doi:10.1016/j.joca.2015.02.021.
5. Lohmander LS, Östenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum.* 2004;50(10):3145-3152. doi:10.1002/art.20589.
6. Froholdt A, Olsen OE, Bahr R. Low risk of injuries among children playing organized soccer. A prospective cohort study. *Am J Sports Med.* 2009;37(6):1155-1160. doi:10.1177/0363546508330132.
7. Price RJ, Hawkins RD, Hulse MA, Hodson A. The Football Association medical research programme: an audit of injuries in academy youth football. *Br J Sports Med.* 2004;38(4):466-471. doi:10.1136/bjism.2003.005165.
8. Myer GD, Ford KR, Brent JL, Hewett TE. Differential neuromuscular training effects on ACL injury risk factors in “high-risk” versus “low-risk” athletes. *BMC Musculoskelet Disord.* 2007;8(1):39. doi:10.1186/1471-2474-8-39.
9. Noyes FR, Barber-Westin SD, Smith ST, Campbell T, Garrison TT. A training program to improve neuromuscular and performance indices in female high school basketball players. *J Strength Cond Res.* 2012;26(3):709-719. doi:10.1519/JSC.0b013e318228194c.

10. Lim BO, Lee YS, Kim JG, An KO, Yoo J, Kwon YH. Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. *Am J Sport Med.* 2009;37(9):1728-1734.
doi:10.1177/0363546509334220.
11. Hewett TE, Lindenfeld TN, Riccobene J V, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med.* 1999;27(6):699-706.
12. Gilchrist J, Mandelbaum BR, Melancon H, et al. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *Am J Sports Med.* 2008;36(8):1476-1483.
13. Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes. 2-year follow-up. *Am J Sports Med.* 2005;33(7):1003-1010.
doi:10.1177/0363546504272261.
14. 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.
doi:10.1097/01.blo.0000026962.51742.99.
15. Myer GD, Ford KR, Hewett TE. Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *J Athl Train.* 2004;39(4):352-364.
16. Dill KE, Begalle RL, Frank BS, Zinder SM, Padua DA. Altered knee and ankle kinematics during squatting in those with limited weight-bearing-lunge ankle-dorsiflexion range of motion. *J Athl Train.* 2014;49(6):723-732. doi:10.4085/1062-6050-49.3.29.
17. Lima YL, Ferreira VMLM, de Paula Lima PO, Bezerra MA, de Oliveira RR, Almeida GPL. The association of ankle dorsiflexion range of motion and dynamic knee valgus: A systematic review and meta-analysis. *Phys Ther Sport.* 2018;29(1):61-69.

doi:10.1016/j.ptsp.2017.07.003.

18. McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. *Med Sci Sport Exerc.* 1999;31(7):959-968.
19. Munro A, Herrington L, Carolan M. Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. *J Sport Rehabil.* 2012;21(1):7-11.
20. Stensrud S, Myklebust G, Kristianslund E, Bahr R, Krosshaug T. Correlation between two-dimensional video analysis and subjective assessment in evaluating knee control among elite female team handball players. *Br J Sports Med.* 2010;45(7):589-595.
doi:10.1136/bjism.2010.078287.
21. Claiborne TL, Armstrong CW, Gandhi V, Pincivero DM. Relationship between hip and knee strength and knee valgus during a single leg squat. *J Appl Biomech.* 2006;22(1):41-50.
22. Crossley KM, Zhang W-J, Schache A, Bryant A, Cowan SM. Performance on the single-leg squat task indicates hip abductor muscle function. *Am J Sports Med.* 2011;39(4):866-873.
doi:10.1177/0363546510395456.
23. DiMattia MA, Livengood AL, Uhl TL, Mattacola CG, Malone TR. What are the validity of the single-leg-squat test and its relationship to hip-abduction strength? *J Sport Rehabil.* 2005;14(2):108-123. doi:10.1123/jsr.14.2.108.
24. Bittencourt N, Ocarino JM, Mendonça LDM, Hewett TE, Fonseca ST. Foot and hip contributions to high frontal plane knee projection angle in athletes: a classification and regression tree approach. *J Orthop Sport Phys Ther.* 2012;42(12):996-1005.
doi:10.2519/jospt.2012.4041.
25. Mauntel TC, Begalle RL, Cram TR, et al. The effects of lower extremity muscle activation and passive range of motion on single leg squat performance. *J Strength Cond Res.* 2013;27(7):1813-1823. doi:10.1519/JSC.0b013e318276b886.

26. Stickler L, Finley M, Gulgin H. Relationship between hip and core strength and frontal plane alignment during a single leg squat. *Phys Ther Sport*. 2015;16(1):66-71.
doi:10.1016/j.ptsp.2014.05.002.
27. Willson J, Ireland ML, Davis I. Core strength and lower extremity alignment during single leg squats. *Med Sci Sport Exerc*. 2006;38(5):945-952.
doi:10.1249/01.mss.0000218140.05074.fa.
28. Agresta CE, Church C, Henley J, Duer T, O'Brien K. Single leg squat performance in active adolescents age 8 to 17 years. *J Strength Cond Res*. 2016;31(5):1187-1191.
doi:10.1519/JSC.0000000000001617.
29. Räisänen AM, Pasanen K, Krosshaug T, et al. Association between frontal plane knee control and lower extremity injuries: a prospective study on young team sport athletes. *BMJ Open Sport Exerc Med*. 2018;4(1):4:e000311. doi:10.1136/bmjsem-2017-000311.
30. Räisänen A, Pasanen K, Krosshaug T, Avela J, Perttunen J, Parkkari J. Single-leg squat as a tool to evaluate young athletes' frontal plane knee control. *Clin J Sport Med*. 2016;26(6):478-482. doi:10.1097/JSM.0000000000000288.
31. Pasanen K, Rossi MT, Parkkari J, et al. Predictors of lower extremity injuries in team sports (PROFITS-study): a study protocol. *BMJ Open Sport Exerc Med*. 2015;1(1):e000076.
doi:10.1136/bmjsem-2015-000076.
32. Fuller CW, Ekstrand J, Junge A, et al. Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Br J Sports Med*. 2006;40(3):193-201. doi:10.1136/bjsm.2005.025270.
33. Bahr R, Holme I. Risk factors for sports injuries—a methodological approach. *Br J Sports Med*. 2003;37(5):384-392. doi:10.1136/bjsm.37.5.384.
34. Cole TJ, Flegal KM, Nicholls D, Jackson A. Body mass index cut offs to define thinness in children and adolescents. *BMJ*. 2007;335(7612):194.

35. Cole TJ, Bellizzi MC, Flegal KM, Dietz WH. Establishing a standard definition for child overweight and obesity worldwide: international survey. *BMJ*. 2000;320(7244):1240. doi:10.1136/bmj.320.7244.1240.
36. Padua DA, DiStefano LJ, Beutler AI, De La Motte SJ, DiStefano MJ, Marshall SW. The Landing Error Scoring System as a screening tool for an anterior cruciate ligament injury-prevention program in elite-youth soccer athletes. *J Athl Train*. 2015;50(6):589-595. doi:10.4085/1062-6050-50.1.10.
37. Emery CA. Risk factors for injury in child and adolescent sport: a systematic review of the literature. *Clin J Sport Med*. 2003;13(4):256-268. doi:10.1097/00042752-200307000-00011.
38. Rössler R, Junge A, Chomiak J, Dvorak J, Faude O. Soccer injuries in players aged 7 to 12 years: a descriptive epidemiological study over 2 seasons. *Am J Sports Med*. 2016;44(2):309-317. doi:10.1177/0363546515614816.
39. 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. doi:10.1177/0363546504269591.
40. Paterno M V, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010;38(10):1968-1978. doi:10.1177/0363546510376053.
41. Söderman K, Alfredson H, Pietilä T, Werner S. Risk factors for leg injuries in female soccer players: A prospective investigation during one out-door season. *Knee Surgery, Sport Traumatol Arthrosc*. 2001;9(5):313-321. doi:10.1007/s001670100228.
42. Emery CA, Meeuwisse WH, Hartmann SE. Evaluation of risk factors for injury in adolescent soccer: implementation and validation of an injury surveillance system. *Am J Sports Med*. 2005;33(12):1882-1891. doi:10.1177/0363546505279576.

43. Rössler R, Junge A, Chomiak J, et al. Risk factors for football injuries in young players aged 7 to 12 years. *Scand J Med Sci Sports*. 2017;September18 [epub ahead of print]. doi:10.1111/sms.12981.
44. Holden S, Boreham C, Doherty C, Delahunt E. Two-dimensional knee valgus displacement as a predictor of patellofemoral pain in adolescent females. *Scand J Med Sci Sports*. 2017;27(2):188-194. doi:10.1111/sms.12633.
45. 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):2325967117733963. doi:10.1177/2325967117733963.
46. Leppänen M, Pasanen K, Kujala U, et al. Stiff landings are associated with increased ACL injury risk in young female basketball and floorball players. *Am J Sports Med*. 2017;45(2):386-393. doi:10.1177/0363546516665810.
47. Zeller B, McCrory JL, Kibler WB, Uhl TL. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med*. 2003;31(3):449-456.
48. Whatman C, Hume P, Hing W. Kinematics during lower extremity functional screening tests in young athletes - Are they reliable and valid? *Phys Ther Sport*. 2013;14(2):87-93. doi:10.1016/j.ptsp.2012.06.001.

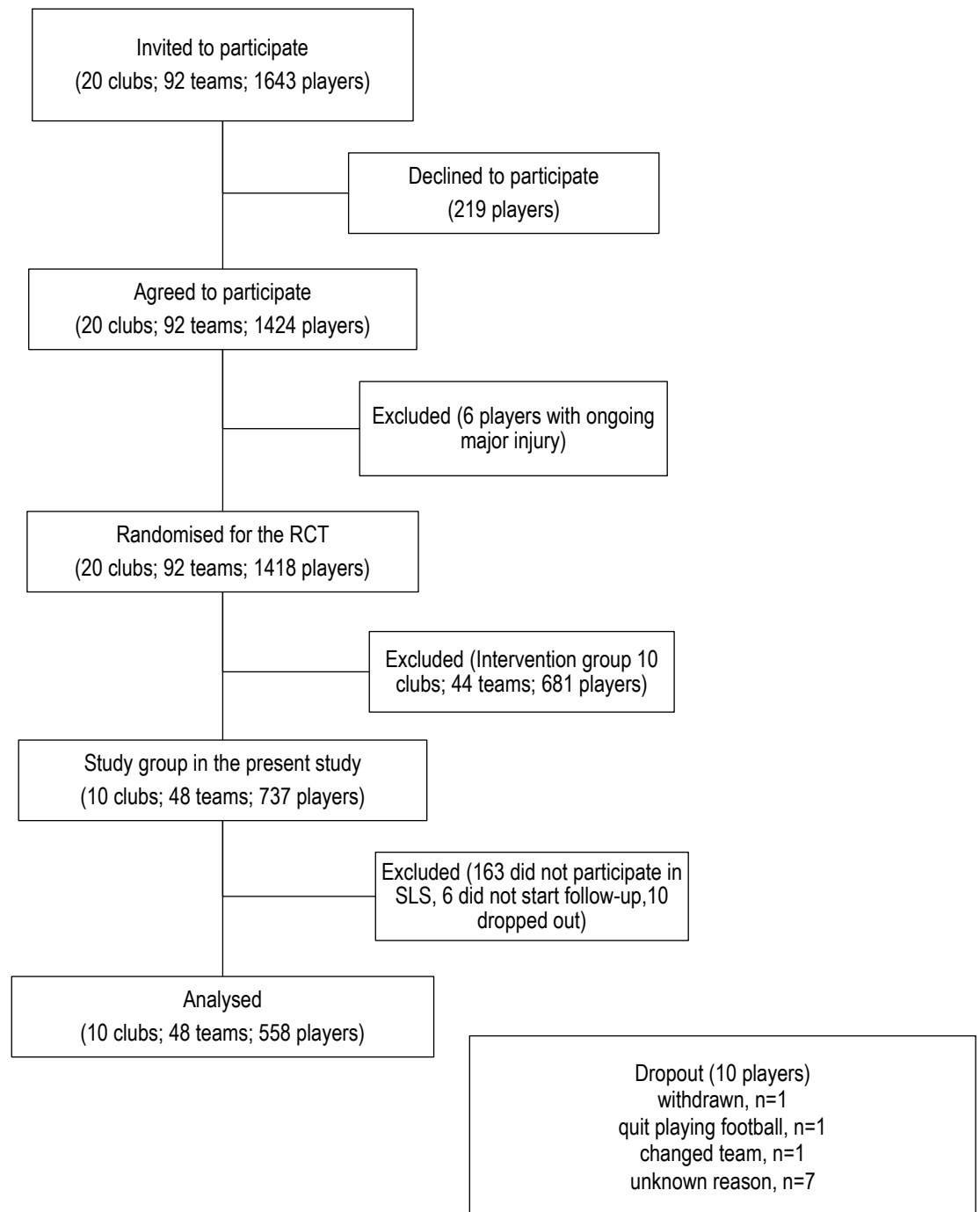


Figure 1. Number of players in each stage of the study

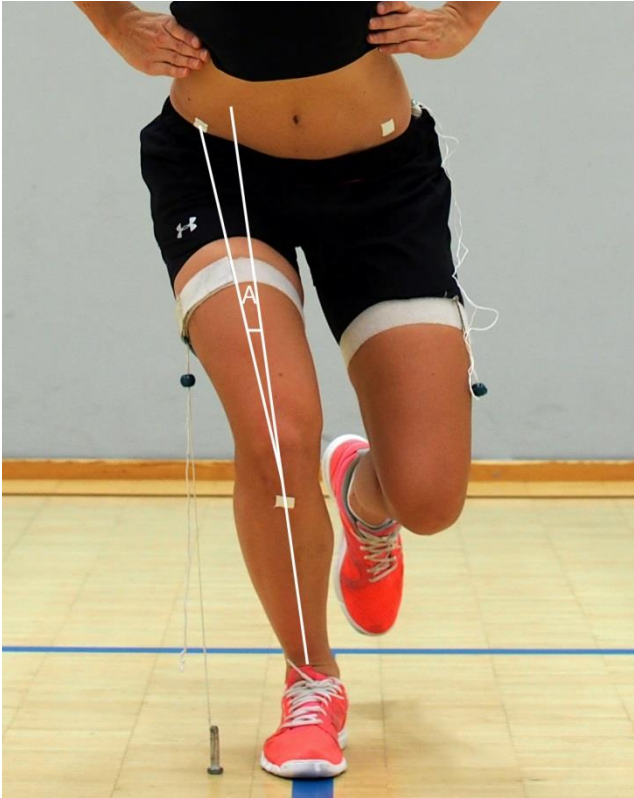


Figure 2. The frontal plane knee projection angle (A) measured during the single-leg squat

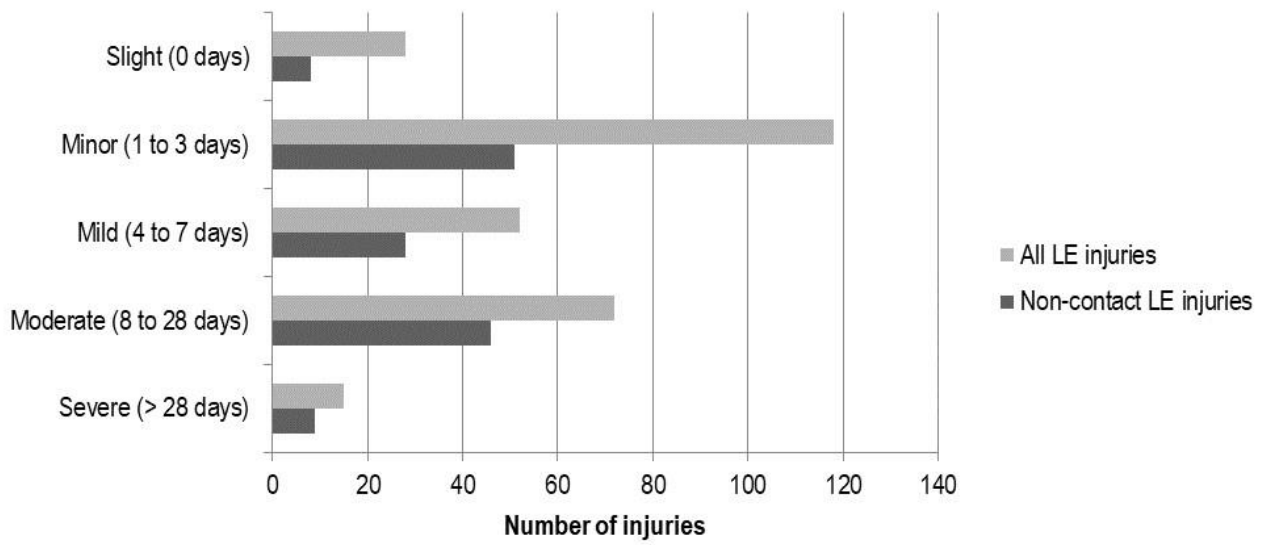


Figure 3. Number of acute lower extremity and acute non-contact lower extremity injuries by severity

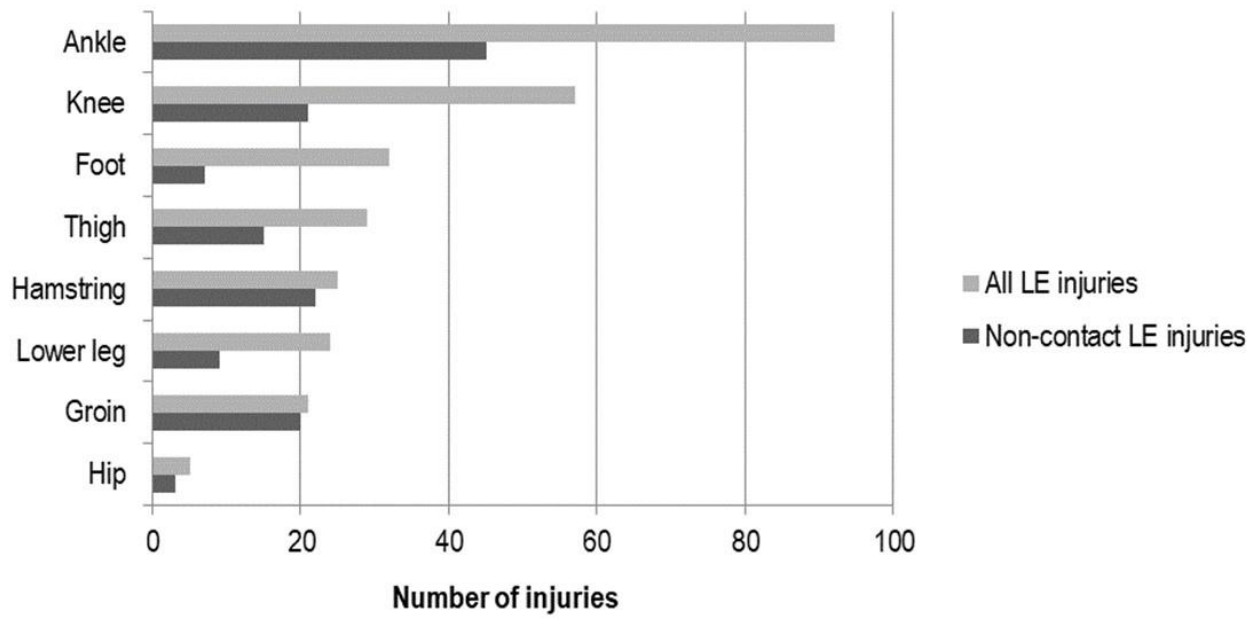


Figure 4. Number of acute lower extremity and acute non-contact lower extremity injuries according to anatomical locations

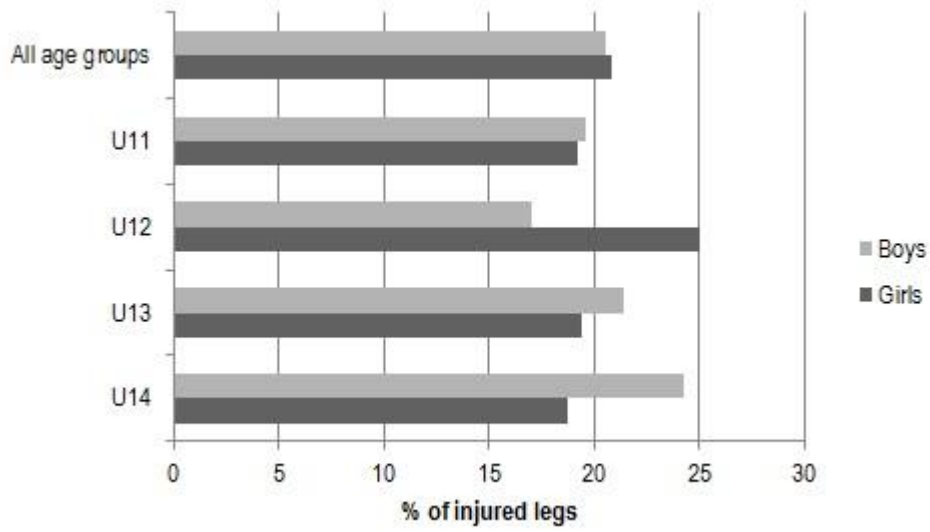


Figure 5. Proportion of injured legs for boys and girls and in each age group

Table 1. Baseline characteristics of the players (mean presented with standard deviation)

Age group	n	Height (cm)	Weight (kg)	BMI	Playing football (years)	FPKPA (°)
Boys	445	151.6 (9.9)	41.1 (8.7)	17.7 (1.9)	6.5 (1.7)	16.5 (12.6)
U11	117	143.3 (6.5)	34.9 (5.3)	16.9 (1.6)	5.1 (1.2)	17.6 (13.5)
U12	105	148.5 (6.5)	38.0 (5.1)	17.2 (1.5)	6.1 (1.2)	17.5 (13.5)
U13	116	154.0 (7.8)	43.3 (6.6)	17.8 (1.8)	6.8 (1.5)	17.0 (12.0)
U14	107	161.7 (8.3)	49.9 (9.2)	18.9 (2.2)	8.0 (1.3)	14.2 (11.5)
Girls	113	151.7 (9.2)	41.6 (7.7)	17.9 (1.7)	5.3 (1.6)	15.4 (10.7)
U11	26	140.5 (4.1)	33.1 (3.9)	16.7 (1.5)	4.2 (1.5)	15.0 (9.8)
U12	32	149.1 (6.4)	39.9 (5.8)	17.9 (1.4)	5.0 (1.0)	19.2 (11.3)
U13	31	157.3 (5.9)	45.6 (5.9)	18.3 (1.6)	5.7 (1.5)	14.2 (11.4)
U14	24	159.6 (5.9)	47.8 (5.3)	18.7 (1.5)	6.2 (1.8)	12.2 (8.3)

BMI=body mass index, FPKPA=frontal plane knee projection angle

Table 2. Univariate analyses of the potential risk factor for acute lower extremity injuries. Odds ratios (OR) presented with 95% confidence interval (CI). N refers to number of legs in the analysis.

Intrinsic factors	n (injured)	OR	95% CI	P value
Categorical variables				
Boy	884 (183)	1		
Girl	226 (47)	0.94	0.63 to 1.40	0.75
Age, intermediate	650 (133)	1		
Age, low (<10.8 years)	236 (46)	0.93	0.64 to 1.35	0.70
Age, high (>13.2 years)	224 (51)	1.13	0.78 to 1.63	0.51
Height, intermediate	726 (152)	1		
Height, low (<142.3 cm)	186 (33)	0.81	0.53 to 1.23	0.32
Height, high (>161.1 cm)	172 (40)	1.13	0.76 to 1.68	0.56
Weight, intermediate	702 (148)	1		
Weight, low (<33.9 kg)	204 (34)	0.75	0.49 to 1.13	0.16 *
Weight, high (>49.3 kg)	178 (43)	1.17	0.79 to 1.73	0.43
BMI, healthy	984 (211)	1		
BMI, low	58 (7)	0.53	0.24 to 1.19	0.12 *
BMI, overweight	40 (7)	0.83	0.36 to 1.92	0.67
FPKPA, intermediate	622 (126)	1		
FPKPA, low (<4.0°)	154 (36)	1.19	0.78 to 1.82	0.42
FPKPA, high (>28.4°)	163 (34)	1.03	0.67 to 1.58	0.90
Able to perform valid SLS	938 (196)	1		
Unable to perform valid SLS	162 (31)	0.90	0.59 to 1.38	0.63
FPKPA asymmetry, intermediate	574 (124)	1		
FPKPA asymmetry, low (<2.6°)	132 (25)	0.86	0.53 to 1.39	0.54
FPKPA asymmetry, high (>18.8°)	148 (28)	0.84	0.53 to 1.33	0.46
Continuous variables				
Age (years)	1110 (230)	1.08	0.96 to 1.23	0.22
Height (cm)	1084 (225)	1.01	1.00 to 1.03	0.15 *
Weight (kg)	1082 (225)	1.02	1.00 to 1.03	0.08 *
BMI	1082 (225)	1.05	0.98 to 1.14	0.19 *
FPKPA (°)	938 (196)	1.00	0.99 to 1.01	0.95
FPKPA asymmetry (°)	898 (164)	1.00	0.98 to 1.03	0.67

BMI=body mass index, FPKPA=frontal plane knee projection angle, SLS=single-leg squat

Table 3. Multivariate analyses of the potential risk factors for all acute lower extremity injuries for all subjects and boys. Adjusted odds ratios (OR) presented with 95% confidence interval (CI). The variables achieving $P < 0.20$ in univariate analyses were analysed. N refers to number of legs in the analysis.

Intrinsic factors	n (injured)	OR	95% CI	<i>P</i> value
All subjects				
Height (cm)	1084 (225)	1.00	0.96 to 1.04	0.96
Weight (kg)	1082 (225)	1.02	0.97 to 1.06	0.46
BMI, healthy	984 (211)	1		
BMI, low	58 (7)	0.60	0.25 to 1.39	0.23
BMI, overweight	40 (7)	0.66	0.245 to 1.74	0.40
Boys				
Height, intermediate	614 (128)	1		
Height, low (<141.7 cm)	128 (19)	0.86	0.44 to 1.68	0.65
Height, high (>161.5 cm)	126 (31)	1.13	0.59 to 2.14	0.72
Weight, intermediate	636 (133)	1		
Weight, low (<32.4 kg)	104 (14)	0.65	0.31 to 1.34	0.24
Weight, high (>49.8 kg)	128 (31)	1.10	0.58 to 2.07	0.79
Age (years)	884 (183)	1.01	0.85 to 1.21	0.89

BMI=body mass index

Table 4. Univariate analyses of the potential risk factor for acute non-contact lower extremity injuries. Odds ratios (OR) presented with 95% confidence interval (CI). N refers to number of legs in the analysis.

Intrinsic factors	n (injured)	OR	95% CI	P value
Categorical variables				
Boy	884 (95)	1		
Girl	226 (28)	1.15	0.72 to 1.83	0.57
Age, intermediate	650 (69)	1		
Age, low (<10.8 years)	236 (27)	1.08	0.67 to 1.73	0.75
Age, high (>13.2 years)	224 (27)	1.14	0.71 to 1.83	0.59
Height, intermediate	726 (78)	1		
Height, low (<142.3 cm)	186 (20)	0.99	0.59 to 1.68	0.98
Height, high (>161.1 cm)	172 (22)	1.19	0.72 to 1.98	0.50
Weight, intermediate	702 (75)	1		
Weight, low (<33.9 kg)	204 (22)	1.00	0.60 to 1.66	0.99
Weight, high (>49.3 kg)	178 (23)	1.22	0.74 to 2.01	0.42
BMI, healthy	984 (116)	1		
BMI, low	58 (2)	0.27	0.07 to 1.13	0.07 *
BMI, overweight	40 (2)	0.41	0.10 to 1.71	0.22
FPKPA, intermediate	6272(66)	1		
FPKPA, low (<4.0°)	154 (17)	1.07	0.60 to 1.89	0.82
FPKPA, high (>28.4°)	163 (19)	1.09	0.63 to 1.87	0.77
Able to perform valid SLS	938 (102)	1		
Unable to perform valid SLS	162 (18)	1.04	0.61 to 1.76	0.90
FPKPA asymmetry, intermediate	574 (69)	1		
FPKPA asymmetry, low (<2.6°)	132 (17)	1.10	0.62 to 1.94	0.75
FPKPA asymmetry, high (>18.8°)	148 (12)	0.65	0.34 to 1.23	0.18 *
Continuous variables				
Age (years)	1110 (123)	1.02	0.87 to 1.19	0.85
Height (cm)	1084 (120)	1.00	0.98 to 1.02	0.92
Weight (kg)	1082 (120)	1.00	0.98 to 1.03	0.79
BMI	1082 (120)	1.01	0.91 to 1.12	0.87
FPKPA (°)	938 (102)	1.00	0.98 to 1.02	0.92
FPKPA asymmetry (°)	798 (89)	0.99	0.96 to 1.02	0.43

BMI=body mass index, FPKPA=frontal plane knee projection angle, SLS=single-leg squat

Table 5. Multivariate analyses of potential risk factors for non-contact lower extremity injuries for all subjects, boys and girls. Adjusted odds ratios (OR) presented with 95% confidence interval (CI). The variables achieving $P < 0.20$ in univariate analyses were analysed. N refers to number of legs in the analysis.

Intrinsic factors	n (injured)	OR	95% CI	<i>P</i> value
All subjects				
BMI, healthy	984 (116)	1		
BMI, low	58 (2)	0.4	0.09 to 1.70	0.21
BMI, overweight	40 (2)	0.00	0.00 to 0.00	0.99
FPKPA asymmetry, intermediate	574 (69)	1		
FPKPA asymmetry, low ($<2.6^\circ$)	132 (17)	1.13	0.64 to 2.02	0.68
FPKPA asymmetry, high ($>18.8^\circ$)	148 (12)	0.679	0.35 to 1.30	0.24
Boys				
FPKPA asymmetry, intermediate	450 (53)	1		
FPKPA asymmetry, low ($<2.5^\circ$)	98 (13)	1.13	0.60 to 2.23	0.67
FPKPA asymmetry, high ($>19.5^\circ$)	102 (7)	0.59	0.26 to 1.35	0.21
BMI, healthy	784 (88)	1		
BMI, low	48 (2)	0.6	0.14 to 2.59	0.49
BMI, overweight	34 (2)	0.00	0.00 to 0.00	0.98
Girls				
Weight, intermediate	134 (13)	1		
Weight, low (<34.0 kg)	40 (8)	2.50	0.93 to 6.71	0.07
Weight, high (>49.2 kg)	42 (7)	1.43	0.48 to 4.31	0.52
Able to perform valid SLS	212 (23)	1		
Unable to perform valid SLS	11 (3)	2.93	0.67 to 12.78	0.15

BMI=body mass index, FPKPA=frontal plane knee projection angle, SLS=single-leg squat

Table 6. Mean frontal plane knee projection angles (FPKPA) by sex and age group. P values are presented for the comparisons of right and left leg and dominant and non-dominant leg FPKPA.

Sex and age group	Mean FPKPA right leg (SD)	Mean FPKPA left leg (SD)	<i>P</i> value	Mean FPKPA dominant leg (SD)	Mean FPKPA non-dominant leg (SD)	<i>P</i> value
Boys	19.6 (12.2)	13.4 (12.3)	<0.001	19.2 (12.1)	13.8 (12.6)	<0.001
U11	20.1 (13.2)	14.9 (13.5)	<0.001	19.4 (13.2)	15.6 (13.8)	0.004
U12	18.8 (13.3)	16.2 (13.6)	0.04	19.1 (13.1)	15.8 (13.8)	0.02
U13	21.1 (11.7)	12.7 (10.7)	<0.001	20.8 (11.4)	13.2 (11.3)	<0.001
U14	18.2 (10.7)	10.0 (10.7)	<0.001	17.3 (10.9)	10.8 (11.1)	<0.001
Girls	17.2 (9.5)	13.5 (11.5)	<0.001	17.1 (10.2)	13.6 (10.9)	0.001
U11	19.0 (7.4)	10.8 (10.3)	<0.001	19.0 (7.4)	10.8 (10.3)	<0.001
U12	19.9 (10.0)	18.5 (12.6)	0.69	20.6 (11.3)	17.8 (11.3)	0.21
U13	15.9 (10.2)	12.6 (12.5)	0.06	15.1 (11.1)	13.4 (11.9)	0.24
U14	13.3 (9.1)	11.1 (7.5)	0.29	13.0 (8.5)	11.5 (8.3)	0.49

FPKPA=frontal plane knee projection angle, SD= standard deviation

SUPPLEMENTARY FILES

Appendix table 1. Univariate odds ratios (OR) for new acute lower extremity injury for boys presented with 95% confidence interval (CI). N refers to the number of legs in the analysis.

Intrinsic factors	n (injured)	OR	95% CI	P value
Categorical variables				
Age, intermediate	502 (100)	1		
Age, low (<10.8 years)	200 (40)	0.99	0.65 to 1.49	0.95
Age, high (>13.2 years)	182 (43)	1.23	0.82 to 1.85	0.33
Height, intermediate	614 (128)	1		
Height, low (<141.7 cm)	128 (19)	0.67	0.39 to 1.14	0.14 *
Height, high (>161.5 cm)	126 (31)	1.23	0.78 to 1.93	0.38
Weight, intermediate	636 (133)	1		
Weight, low (<32.4 kg)	104 (14)	0.58	0.32 to 1.05	0.07 *
Weight, high (>49.8 kg)	128 (31)	1.22	0.78 to 1.91	0.39
BMI, healthy	784 (165)	1		
BMI, low	48 (7)	0.72	0.32 to 1.64	0.43
BMI, overweight	34 (6)	0.94	0.38 to 2.33	0.89
FPKPA, intermediate	470 (97)	1		
FPKPA, low (<3.9°)	121 (29)	1.20	0.74 to 1.93	0.46
FPKPA, high (>29.1°)	136 (28)	0.98	0.61 to 1.58	0.94
Able to perform valid SLS	726 (154)	1		
Unable to perform valid SLS	151 (28)	0.85	0.54 to 1.34	0.49
FPKPA asymmetry, intermediate	450 (98)	1.00		
FPKPA asymmetry, low (<2.5°)	98 (19)	0.85	0.49 to 1.47	0.56
FPKPA asymmetry, high (>19.5°)	102 (18)	0.76	0.43 to 1.33	0.33
Continuous variables				
Age (years)	884 (183)	1.12	0.97 to 1.28	0.12 *
Height (cm)	868 (178)	1.01	1.00 to 1.03	0.16 *
Weight (kg)	866 (178)	1.02	1.00 to 1.04	0.09 *
BMI	866 (178)	1.05	0.97 to 1.15	0.23
FPKPA (°)	726 (154)	1.00	0.99 to 1.02	0.98
FPKPA asymmetry (°)	610 (126)	1.01	0.98 to 1.03	0.62

BMI=body mass index, FPKPA=frontal plane knee projection angle, SLS=single-leg squat

Appendix table 2. Univariate odds ratios (OR) for new acute lower extremity injury for girls presented with 95% confidence interval (CI). N refers to the number of legs in the analysis.

Intrinsic factors	n (injured)	OR	95% CI	<i>P</i> value
Categorical variables				
Age, intermediate	132 (29)	1		
Age, low (<10.9 years)	48 (9)	0.82	0.35 to 1.89	0.64
Age, high (>13.1 years)	46 (9)	0.91	0.39 to 2.12	0.83
Height, intermediate	136 (30)	1		
Height, low (<142.5 cm)	44 (10)	1.02	0.45 to 2.31	0.96
Height, high (>160.9 cm)	36 (7)	0.84	0.33 to 2.11	0.70
Weight, intermediate	134 (26)	1		
Weight, low (<34.0 kg)	40 (10)	1.36	0.59 to 3.15	0.47
Weight, high (>49.2 kg)	42 (11)	1.45	0.64 to 3.28	0.37
BMI, healthy	200 (46)	1		
BMI, low	10 (0)	0.10	0.00 to 4.13	0.22
BMI, overweight	6 (1)	0.66	0.07 to 5.86	0.71
FPKPA, intermediate	145 (29)	1		
FPKPA, low (<4.7°)	35 (7)	0.97	0.39 to 2.49	0.97
FPKPA, high (>26.1°)	32 (6)	0.91	0.34 to 2.42	0.84
Able to perform valid SLS	212 (42)	1		
Unable to perform valid SLS	11 (3)	1.50	0.38 to 5.95	0.56
FPKPA asymmetry, intermediate	132 (28)	1.00		
FPKPA asymmetry, low (<2.6°)	34 (6)	0.86	0.32 to 2.30	0.76
FPKPA asymmetry, high (>18.8°)	38 (8)	0.99	0.41 to 2.42	0.99
Continuous variables				
Age (years)	226 (47)	0.95	0.71 to 1.28	0.75
Height (cm)	216 (47)	1.01	0.97 to 1.04	0.76
Weight (kg)	216 (47)	1.01	0.97 to 1.06	0.52
BMI	216 (47)	1.09	0.89 to 1.33	0.40
FPKPA (°)	212 (42)	1.00	0.97 to 1.03	0.89
FPKPA asymmetry (°)	188 (38)	1.00	0.95 to 1.05	0.92

BMI=body mass index, FPKPA=frontal plane knee projection angle, SLS=single-leg squat

Appendix table 3. Univariate odds ratios (OR) for new acute non-contact lower extremity injury for boys presented with 95% confidence interval (CI). N refers to the number of legs in the analysis.

Intrinsic factors	n (injured)	OR	95% CI	P value
Categorical variables				
Age, intermediate	502 (49)	1		
Age, low (<10.8 years)	200 (23)	1.20	0.71 to 2.03	0.50
Age, high (>13.2 years)	182 (23)	1.32	0.78 to 2.25	0.30
Height, intermediate	614 (64)	1		
Height, low (<141.7 cm)	128 (11)	0.82	0.42 to 1.60	0.55
Height, high (>161.5 cm)	126 (17)	1.33	0.75 to 2.36	0.34
Weight, intermediate	636 (67)	1		
Weight, low (<32.4 kg)	104 (9)	0.80	0.39 to 1.66	0.55
Weight, high (>49.8 kg)	128 (16)	1.21	0.68 to 2.17	0.52
BMI, healthy	784 (88)	1		
BMI, low	48 (2)	0.35	0.08 to 1.48	0.16 *
BMI, overweight	34 (2)	0.52	0.12 to 2.22	0.38
FPKPA, intermediate	470 (52)	1		
FPKPA, low (<3.9°)	121 (13)	0.95	0.50 to 1.82	0.89
FPKPA, high (>29.1°)	136 (14)	0.92	0.49 to 1.71	0.78
Able to perform valid SLS	726 (79)	1		
Unable to perform valid SLS	151 (15)	0.91	0.51 to 1.63	0.75
FPKPA asymmetry, intermediate	450 (53)	1		
FPKPA asymmetry, low (<2.5°)	98 (13)	1.13	0.59 to 2.17	0.71
FPKPA asymmetry, high (>19.5°)	102 (7)	0.56	0.24 to 1.27	0.16 *
Continuous variables				
Age (years)	884 (95)	1.08	0.90 to 1.29	0.41
Height (cm)	868 (92)	1.01	0.99 to 1.03	0.55
Weight (kg)	866 (92)	1.01	0.98 to 1.03	0.50
BMI	866 (92)	1.02	0.92 to 1.15	0.69
FPKPA (°)	726 (79)	1.00	0.98 to 1.02	0.90
FPKPA asymmetry (°)	610 (66)	0.98	0.96 to 1.02	0.30

BMI=body mass index, FPKPA=frontal plane knee projection angle, SLS=single-leg squat

Appendix table 4. Univariate odds ratios (OR) for new acute non-contact lower extremity injury for girls presented with 95% confidence interval (CI). N refers to the number of legs in the analysis.

Intrinsic factors	n (injured)	OR	95% CI	P value
Categorical variables				
Age, intermediate	132 (17)	1		
Age, low (<10.9 years)	48 (7)	1.15	0.44 to 2.99	0.77
Age, high (>13.1 years)	46 (4)	0.68	0.21 to 2.15	0.51
Height, intermediate	136 (16)	1		
Height, low (<142.5 cm)	44 (8)	1.64	0.65 to 4.17	0.30
Height, high (>160.9 cm)	36 (4)	0.92	0.29 to 2.97	0.89
Weight, intermediate	134 (13)	1		
Weight, low (<34.0 kg)	40 (8)	2.29	0.87 to 6.04	0.09 *
Weight, high (>49.2 kg)	42 (7)	1.83	0.67 to 4.98	0.23
BMI, healthy	200 (28)	1		
BMI, low	10 (0)	0.00	0.00 to 0.00	1.00
BMI, overweight	6(0)	0.00	0.00 to 0.00	1.00
FPKPA, intermediate	145 (16)	1		
FPKPA, low (<4.7°)	35 (3)	0.77	0.21 to 2.76	0.69
FPKPA, high (>26.1°)	32 (4)	1.13	0.35 to 3.64	0.84
Able to perform valid SLS	212 (23)	1		
Unable to perform valid SLS	11 (3)	3.09	0.76 to 12.6	0.12 *
FPKPA asymmetry, intermediate	132 (16)	1		
FPKPA asymmetry, low (<2.6°)	34 (4)	1.04	0.32 to 3.36	0.95
FPKPA asymmetry, high (>18.8°)	38 (5)	1.10	0.37 to 3.24	0.86
Continuous variables				
Age (years)	226 (28)	0.79	0.55 to 1.14	0.20
Height (cm)	216 (28)	0.98	0.94 to 1.02	0.34
Weight (kg)	216 (28)	0.98	0.93 to 1.03	0.43
BMI	216 (28)	0.94	0.74 to 1.20	0.64
FPKPA (°)	212 (23)	1.00	0.97 to 1.05	0.83
FPKPA asymmetry (°)	188 (23)	1.01	0.96 to 1.08	0.64

BMI=body mass index, FPKPA=frontal plane knee projection angle, SLS=single-leg squat