Functional Contributions to Lower Extremity Musculoskeletal Injury in High School Soccer and Basketball Athletes

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

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2018

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Abstract

Approximately 7.8 million high school students participate in athletics annually and although athletic participation comes with many benefits, it also comes with an inherent risk of lower extremity (LE) musculoskeletal (MSK) injury. Effectively identifying individuals at greatest risk of injury first requires an accurate understanding of injury risk. Despite the breadth of research, current injury risk assessment models are inadequate and no gold standard exists for effectively identifying risk of injury in physically active populations. Most research fails to target multiple risk factors and, instead, often focuses on how one specific risk factor alters injury risk. Additionally, research has not examined how injury risk is altered by relationships among risk factors. These gaps in knowledge have formed an understanding of injury risk that does not reflect a multi-factorial model where factors influence risk through a combination of direct, indirect and moderated effects. Therefore, the purpose of this research was to assess the complex multifactorial nature of LE MSK injury risk in adolescent athletes.

Aim 1 established similarities and differences in epidemiology of injury in boys' and girls' high school soccer and basketball using a national injury surveillance system. The results of this aim indicated that injury rates are greater in soccer than basketball, and greater in competitions than practices, regardless of sex. The most common injuries were similar between sports, suggesting both sports should emphasize preventing sprains and strains affecting the ankle and knee, specifically those resulting from player contact and

noncontact mechanisms. Additional efforts are also needed to prevent hip and thigh/upper leg injuries in soccer.

Aim 2 evaluated direct and indirect effects of functional performance asymmetries, as well as drop landing mechanics, on injury in 2,645 high school soccer and basketball players. Results from this aim indicate that ankle dorsiflexion (DF) range of motion (ROM) limb symmetry index (LSI), single leg anterior reach (SLAR) LSI, anterior single leg hop for distance (SLHOP) LSI, and Impression Landing Error Scoring System performance are neither directly nor indirectly related to odds of LE MSK injury in high school soccer and basketball players. Injury history was directly related to an increased likelihood of future injury.

Aim 3 evaluated whether potential relationships between functional asymmetries and LE injury were moderated by functional performance in 2,645 high school soccer and basketball players. Results from this aim indicate that effects of ankle DF ROM LSI, SLAR LSI, and SLHOP LSI on injury may not be moderated by ankle DF ROM performance, SLAR performance, and SLHOP performance, respectively. Additionally, functional performances may not be directly related to injury independent of functional asymmetries, age, sex, sport, and injury history.

Findings from this study suggest that additional functional performance tests, as well as more sensitive measures of functional performance, should be evaluated in an attempt to better identify individuals at increased risk of injury. The statistically significant relationship between previous injury and future injury highlights the need to obtain accurate injury history during PPEs to identify individuals requiring further medical evaluation to mitigate time loss LE MSK injury.

Dedication

To everyone who has helped me along the way, I am forever grateful.

Acknowledgments

I would like to thank my committee for their continual guidance throughout this process. I would specifically like to acknowledge my advisor and mentor Dr. James Onate who taught me about so much more than just research and opened doors for me I never imagined possible.

I would like to thank my previous mentors Dr. Paul Geisler, Dr. Jay Hertel, and Dr. Joe Hart. You all helped me develop my intellectual curiosity and critical thinking skills. My success at The Ohio State University would not have been possible without your influence.

I would be remiss not to acknowledge the various funding sources that have allowed me to pursue my PhD: The Ohio State University Graduate Fellowship Program, the National Institute of Health, the Department of Defense, and the Injury Prevention Research Laboratory at Uniformed Services University of the Health Sciences.

I also would like to thank my family who have always supported me in any challenge I've faced.

I would like to thank my fellow lab mates whom I could never have done this without: Dr. Dustin Grooms, Dr. Eric Schussler, Meghan Miller, Mike McNally, Cambrie Starkel, Chris Ballance, Maria Talarico, and Matthew Brancaleone.

Lastly, I would like to thank Stephanie Deters. You have provided me continual support and always reminded me there is life outside of research, I cannot thank you enough.

This research was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases of the National Institutes of Health (Award Number 5R01AR062578-02). The content of this manuscript is the responsibility of the authors and does not necessarily reflect the views of the funding agency.

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Fields of Study

Major Field: Health and Rehabilitation Science

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Chapter 1: Aims, Limitations, Delimitations

Approximately 7.8 million high school students participate in athletics annually[1] with a competition musculoskeletal (MSK) injury rate of 4.63 injuries per 1,000 exposures and a practice MSK injury rate of 1.69 injuries per 1,000 exposures.[2] Over half (57.2%) of these injuries affect the lower extremity (LE).[2] These injuries result in high health care costs due to short-term care, as well as long-term care from disability and decreased quality of life.[3] Reducing health care costs and disability, while improving quality of life, can be achieved by establishing a process for effectively preventing LE MSK injury.

Effectively identifying individuals at greatest risk of injury first requires an accurate understanding of injury risk. Various factors such as sex,[4–7] injury history[8–11] and physical performance are found to be associated with increased risk of suffering a LE injury; a variety of physical performance metrics have been assessed including range of motion,[12–14] postural control,[15–20] power generation,[21–23] and neuromuscular control.[24–27] Despite the breadth of research, current injury risk assessment models are inadequate and no gold standard exists for effectively identifying risk of injury in physically active populations.[28,29] Most research fails to target multiple risk factors and, instead, often focuses on how one specific risk factor alters injury risk.[16,30,31] Additionally, research has not examined how injury risk is altered by relationships among risk factors. These gaps in knowledge have formed an understanding of injury risk that does not reflect a multi-factorial model where factors influence risk through a combination of direct, indirect and moderated effects. Thus, there is an unmet need for a multifactorial understanding of injury risk that can be used to improve current injury risk assessment models.

Therefore, the *overall objective* of this research is to assess the complex multifactorial nature of LE MSK injury risk in adolescent athletes. Our *main hypothesis* is that demographics, as well as poor LE range of motion (ROM), postural control, power generation and neuromuscular control, will be related to increased injury risk through a combination of direct, indirect, and moderated effects. The *rationale* behind the proposed research is that establishing a clearer understanding of injury risk will ultimately lead to the development of a gold standard for assessing injury risk, and subsequently improving injury risk prediction and prevention efforts.

AIMS

Aim 1. Describe the epidemiology of LE MSK injury in high school boys' and girls' soccer and basketball.

Aim 2. Identify direct and indirect effects of functional asymmetries on LE MSK injury risk.

Aim 3. Identify how effects of functional asymmetries on LE MSK injury risk vary based on functional performances.

OPERATIONAL DEFINITIONS

- Certified Athletic Trainer (AT): Individual who has satisfactorily completed educational requirements and passed the Board of Certification, Inc. certification examination to practice as an athletic trainer.
- Lower extremity musculoskeletal injury: Injury affecting the lower extremity that required the individual to seek medical care and resulted in loss of participation for at least one practice or competition.
- Ankle dorsiflexion (DF) range of motion (ROM): Assessed using a weight bearing lunge test. Each participant performed two trials per leg to obtain the farthest distance they were able to reach without lifting their heel off the ground. The score was recorded in centimeters as the furthest distance from the wall to the first toe of the stance leg.
- Lower extremity postural control: Assessed with the single leg anterior reach (SLAR) test. The SLAR was conducted using only the anterior direction of the Lower Quarter Y Balance Test (Functional Movement Systems, Danville, VA). Reach distances for each limb were averaged and normalized to leg length (% LL).
- Lower extremity power generation/landing control: Assessed using the anterior, single leg hop for distance (SLHOP) test. Jump distances were measured at the 1st toe to the nearest tenth centimeter. The average of the three trials was then normalized to limb length (% LL).
- Double leg landing mechanics: Assessed using the Impression Landing Error Scoring System (iLESS). The iLESS had two possible scores, 0 or 1, based on

the real-time clinician observation. A score of 0 meant a low risk/excellent movement pattern, while a score of 1 meant a high risk/poor movement pattern. Criteria used to evaluate movement patterns included knee valgus and knee flexion at initial contact, and knee valgus and knee flexion displacement from initial contact to maximum knee flexion.

- Leg length: Distance from the anterior superior iliac spine to the medial malleolus measured in centimeters.

LIMITATIONS

- Only high school athletes were studied so our findings may not be generalizable to other playing levels, such as youth, college, or professional programs.
- Only soccer and basketball were analyzed and therefore results cannot be generalized to additional sports.
- Injuries were limited to time-loss injuries only.
- ATs reported all injuries so underreporting of injuries may have occurred.
- Injury history was self-reported and thus possibly underreported.
- We did not record athlete-exposures for aims 2 and 3, such as numbers of games and practices participated in, due to our concern with our ability to accurately capture exposure data.
- Clinical assessments of range of motion, balance, power generation/control, and neuromuscular control were not isolated assessments designed to measure only their respective factors.

- Functional performance was assessed during the pre-season and may not reflect athletes’ functional performance prior to injury if that injury occurred late in the season.

DELIMITATIONS

- Large sample size provides adequate power for statistical analyses.
- Large sample size allows for training and testing sets to develop and validate statistical models.
- Nationwide sample of high schools allows results to generalize to different parts of the country.
- Simple clinical tests allow results to be applied to a variety of settings regardless of resource or financial constraints.
- Soccer and basketball are commonly sponsored high school sports allowing the results to generalize to a large proportion of high school athletes.

Chapter 2: Literature Review

HISTORY OF INJURY RISK SCREENING

Advocacy for health screening among healthy individuals began as early as 1861 when it was proposed that prior to illness, individuals experience states of "low health" and that intervening during these early stages can prevent the illness from progressing.[32,33] It was proposed that individuals in the states of low health don't often seek medical care and therefore a periodic health examination may help identify individuals who can be treated pre-emptively.[32] By 1922 support for periodic health screenings rose as the American Medical Association (AMA) recommended periodic health examinations among healthy individuals.[34] Their statement was that identifying factors among healthy individuals that may indicate a risk of future illness or the presence of factors that may indicate a previously unidentified condition, can improve short-term and long-term health.[34]

As routine health examinations became more commonplace, screening began to expand to other populations such as military personnel.[32,35–37] In the early to middle 1900s routine medical examinations in the military revealed that a large proportion of young men, often considered healthy, had underlying physical defects not previously identified.[32,37] As a result, health care professionals recommended routine health screenings in the military population. Periodic health examinations also expanded to industry settings where job success was dependent on the health and fitness of the employees.[35,36]

By the mid to late 1900s physical evaluations were recommended prior to participation in athletics.[38,39] In the 1970s the AMA recommended athletes complete a pre-participation physical evaluation (PPE) prior to athletic participation in an attempt to prevent illness and injury, life threatening or otherwise.[39] The state of the pre-participation physical evaluation has changed over the years, typically focusing on health history, cardiovascular assessments, and musculoskeletal (MSK) examinations.[40,41] The MSK examination portion was traditionally a quick orthopedic screen but has since evolved to include a functional component.[41–43] One goal of the MSK examination portion of the PPE is to identify MSK injury risk among athletes prior to participation.[43] The ability for the current examination recommendations to meet this goal, however, has come under scrutiny.[42,44,45] Poor predictive capabilities of the currently recommended functional assessments have led researchers to evaluate additional functional performance measures that may be able to identify individuals at greater risk of injury, particularly lower extremity (LE) MSK injury.[13,17,21,22,24]

INJURY DEFINITIONS

Injury has been defined in numerous ways in scientific literature based on affected region,[11,16,26,46] amount of participation time lost due to the injury,[47,48] whether contact was involved,[15,16] as well as whether the injury was acute or chronic.[12,26,49] These various definitions cause considerable discrepancies in study methodology, affecting external validity.

Structure

Injuries are often defined by the affected structure (e.g. anterior cruciate ligament [ACL], hamstring),[23,26,50] joint (e.g. talocrural),[19,46,51] or region (e.g. lower extremity),[16,21,52,53] which may reduce external validity of study findings. For example, results from studies examining risk factors for ankle injury may not predict total LE injury adequately. Conversely, a neuromuscular control assessment developed to predict any LE injury may predict injury to the knee adequately but perform poorly when generalized to predicting ankle injury.

Mechanism of Injury

Injuries may also be defined by the mechanism of injury (contact, non-contact or both).[21,54–56] It is important to differentiate between contact and non-contact injuries since there may be differential effects of risk factors on each mechanism. Contact injuries may be related to factors such as environmental awareness, strength (to protect against contact), or use of protective equipment.[57] Non-contact injuries may be related to physical function factors such as LE neuromuscular control[26,58] and postural control.[16,17,56] These differences are important to understand because they may have important implications for injury prevention strategies. Contact injuries may benefit from changes to equipment or rules that better protect the individual from contact.

Participation Time

Injury definitions also often include the amount of participation time lost due to the injury. Injury surveillance programs such as High School Reporting Information Online™ (HS-RIO) requires an injury event to result in at least one day of athletic participation lost.[47] Such a definition results in recording of time loss injuries only. However, not all injuries result in time loss and therefore results from such studies may not represent all LE MSK injuries. To include non-time loss injuries, Kerr et al. defines injury as damaged tissue that has been diagnosed as an injury by a medical professional, such as a certified Athletic Trainer (AT) or physician;[48] this definition does not require lost participation time.

Acute or Chronic

Lastly, injuries can be defined as acute or chronic.[22,51,59] Acute conditions are those that occur from one traumatic event, such as anterior cruciate ligament sprains, whereas chronic conditions occur from repetitive micro trauma, such as medial tibial stress syndrome. It is possible that risk factors for acute injuries may differ from those of chronic injuries since the injury mechanisms are different. Risk factors that increase the amount of repetitive micro trauma, such as running frequency, may be a better indicator of chronic conditions than acute conditions; increased running frequency may or may not increase the risk of an acute injury.

INJURY REPORTING

Injury reporting methodology can also vary between research studies. Diagnosis from a medical professional is often all that is required, while some studies require a positive diagnostic test such as from magnetic resonance imaging (MRI).[10,18,26] Injury can also be reported retrospectively or prospectively.[31] Prospective injury reporting is preferred to retrospective designs because patient characteristics are known prior to injury. In retrospective studies, patient characteristics may be assessed at the time of injury or at the time of return to play. The information gleaned from these studies may provide valuable information about injury risk but since researchers cannot determine if the characteristics were present prior to injury their predictive value is unclear.[31] This may raise particular concerns with functional assessments. A retrospective study would not be able to identify if poor LE postural control was present before injury, and therefore a potential risk factor, or if the injury altered proprioception, reducing postural control ability.[60]

INJURY RISK FACTORS

Risk factors for LE MSK injury can vary greatly given the large number of injuries that affect adolescent athletes. A variety of risk factors for LE MSK injury, as operationally defined in this project, have been proposed by researchers.[7,8,17,22,24,26,61,62] Relationships between demographics and physical function characteristics are of particular interest to this proposed project. Physical function characteristics are of interest because they are modifiable factors that can be targeted in strength and conditioning programs, as well as universal injury prevention programs.

Demographic Factors

Numerous demographic variables have been evaluated as risk factors for LE MSK injury.[63–65] Demographic factors include, but are not limited to, age, sex, body mass index (BMI), sport, and injury history.

Age

The role of age in LE MSK injury risk is unclear due to variable findings.[13,63–68] Some researchers have identified injury risk to increase with age,[63–65] while other researchers identified increased injury risk among younger athletes.[66,67] Additionally, age may not be related to LE MSK injury risk in general.[13,68] As a result, the role of age in LE MSK injury risk has not been elucidated. Study results may be inconclusive because age may be an approximate representation of an underlying factor such as physical maturation status. Delayed maturation status may be related to an increased risk of LE injury[69,70] and therefore, age may only be related to injury risk if it accurately represents maturation status.

Sex

Sex is a proposed injury risk factor.[8,71] Females are at higher risk for a variety of LE MSK injuries compared to males, including patellofemoral pain syndrome[72] and anterior cruciate ligament ruptures.[4,73] The relationship between sex and injury may be due to a variety of factors such as hormonal[74–76] or anatomical[77,78] considerations. Females' risk for ACL injury changes throughout their menstrual cycles.[74–76] Additionally, smaller femoral condyle notch width, often found in females,[78] may increase the risk of ACL tears.[77] The relationship between sex and injury may also be due to neuromuscular control. Neuromuscular control is often worse in females,[5,79,80] potentially increasing the risk of injury in this population.[24,26] These findings highlight the importance of sex as an injury risk factor in adolescent athletes.

Body Mass Index

BMI has been proposed as a risk factor for a variety of LE MSK injuries. The exact role of BMI in injury risk is unclear as results are mixed.[63,65,81–83] Jones et al. identified that males with relatively high BMI (above the 75th percentile in their study sample) were more likely to get injured than males in with BMI below the 75th percentile.[81] Knapik et al. however, did not identify a relationship between BMI and MSK injury risk.[65]

Injury History

Injury History is an established injury risk factor.[8,71] Individuals with a history of LE MSK injury are more likely to suffer a future LE MSK injury.[8,84] This has been established for a variety of injuries including those affecting the ankle, knee and hip.[8] The influence of injury history may not only be limited to musculoskeletal injuries. A previous concussion may increase the risk of knee injury due to neurocognitive changes.[52,54,85,86] These findings highlight the importance of injury history as an injury risk factor in adolescent athletes.

Sport

Injury rates vary between sports[87–89] and therefore, participation in specific sports inherently increases the risk of LE MSK injury. The highest risk of LE MSK injury occurs in football.[87–89] Football also has the highest ACL injury rate in high school athletics.[89] Girls' soccer and basketball have the second and third highest ACL injury rates, respectively.[89] The exact reason for differing injury rates between sports is unclear but it may be due to the contact nature of some sports, the increased exposures associated with longer seasons, or gender effects.

Physical Performance Risk Factors

Since our long-term goal is to predict and prevent LE MSK injury, it is important to model an understanding of injury risk that involves modifiable factors that can directly inform prediction and prevention strategies. Physical performance characteristics are of particular focus in this project because they are more easily modifiable. Physical performance characteristics include range of motion (ROM), strength, postural control, power generation, neuromuscular control, and movement quality.

Range of Motion

The role of joint ROM in injury risk is inconclusive as findings have varied between research studies.[7,12,13,82,90–92] When examining relationships between joint specific ROM and injury, it appears that ankle dorsiflexion ROM may be related to injury risk.[12,13,91,93] Soderman et al. identified that increased ankle dorsiflexion ROM asymmetry was associated with an increased risk of overuse leg injury.[13] Kaufman et al. identified a similar relationship.[12] Restricted ankle dorsiflexion ROM may also increase the risk of a lateral ankle sprain.[91] Additionally, individuals with reduced dorsiflexion ROM land from a jump in a more extended posture, potentially increasing the risk of ACL injury.[93] Despite these findings, the true relationship between ankle dorsiflexion ROM and injury is unclear due to contradictory findings.[82,90] Wiesler et al. did not identify an association between ankle ROM and injury in dancers.[90] There may be a relationship between hip range of motion and injury.[94,95] Restricted total hip range of motion may increase the risk of chronic groin injury.[95] Research by Twellaar et al, however, failed to identify a relationships between ROM and hip injury.[82] These findings indicate that ROM may influence injury, although it is difficult to make strong conclusions given variable research findings.

Strength

The relationship between strength and LE MSK injury is unclear.[13,63,91,96–98] Absolute strength may not be related to an increased risk of ankle injury.[9,46,63,92,99] Strength imbalances however, may be related to increased injury risk.[13,98] Soderman et al. identified that strength imbalances increased the risk of lower extremity injury.[13] Baumhauer et al. identified that injury inversion ankle sprain rates are greater among individuals with imbalances between eversion and inversion strength, as well as imbalances between plantarflexion and dorsiflexion strength.[98] Strength imbalances may also increase the risk of knee and thigh injuries.[94,97,100] Imbalance between internal and external rotation may increase the risk of patellofemoral pain syndrome in runners.[100] Imbalances between hamstring and quadriceps peak torque may increase the risk of hamstring strain in professional soccer players.[97] These findings support the potential benefit of strength imbalance as a predictor of various LE MSK injuries.

Postural Control

Lower extremity postural control has been established as a risk factor for LE MSK injury.[16–18,99] McGuine et al. identified that greater center of pressure displacement was associated with a greater risk of lateral ankle sprain.[18] Wang et al. identified similar relationships between postural sway and risk of ankle injury.[99] Researchers have also identified that the risk of general LE injury is greater for individuals with poor postural control as assessed via the Y-Balance test.[17,21,56] Additionally, postural control asymmetry may increase the risk of injury.[17] Specifically asymmetries in the anterior direction of the Lower Quarter Y-Balance Test greater than 4 cm increase injury risk.[17] These findings indicate the importance of postural control as an injury risk factor.

Power Generation

Poor LE power generation is a proposed injury risk factor.[22] Men with poor single leg hop distances are believed to be at a greater risk of LE injury.[22] Additionally, individuals with asymmetric single leg hop distances are believed to be at greater risk of injury; females with greater than a 10% asymmetry in single leg hop distances are at greater risk of ankle injury.[22] Findings from Ostenberg et al. were contradictory however, as power generation assessed via hop tests were not predictive of LE MSK injury in female soccer players.[63] As a result, the true relationship between power generation and acceptance and LE MSK injury risk is unclear.

Neuromuscular Control

Poor LE neuromuscular control is a proposed injury risk factor.[24,26] Increased knee abduction motion and knee abduction moments during a drop vertical jump (DVJ) task may increase risk of ACL injury.[15,26] Additionally, improvements in neuromuscular control following injury prevention programs are associated with reduced ACL injury risk.[101,102] Performance on the Landing Error Scoring System (LESS) scores may also be related to injury.[24] The LESS is an assessment of LE neuromuscular control that scores individuals based on how they land during a DVJ task.[27,103] Poor scores may be related to an increased risk of ACL injury in youth female athletes.[24] The relationship between this assessment of neuromuscular control and injury other than ACL injury does not appear to be supported by research.[27] The value of the LESS in predicting injury risk in other age groups, or among males is also unclear.[27]

Movement Quality

Holistic movement quality has also been proposed as a risk factor for LE MSK injury.[20,21,29,55,61,104–106] Individuals with poor movement quality, as assessed by the Functional Movement Screen, may be at greater risk of LE MSK injury.[29,61,104,105,107] Kiesel et al. and Garrison et al. identified that poor movement quality increased the risk of LE MSK injury among professional football players and college athletes, respectively.[61,107] Additionally, O'Connor et al. identified an increased risk of acute injury in male officer candidates.[105] Movement quality asymmetry may also increase the likelihood of injury.[104] Mokha et al. identified that individuals with an asymmetry on any Functional Movement Screen test were more likely to suffer a LE MSK injury.[104]

Environmental Risk Factors

Although the focus of this project is on demographic and functional performance risk factors for LE MSK injury risk, environmental factors contribute to the complex, multifactorial nature of injury.[14,62,108] Both physical (e.g. playing surface) and social (e.g. parental pressures) environmental factors may contribute to injury risk.

Physical Environment

Playing surface is a physical environment factor that may increase the risk of LE MSK injury.[14,62,109] LE MSK injury rates are higher on turf fields compared with traditional grass fields.[14,109] Hershman et al. identified that knee and ankle injury rates are higher on turf compared with grass.[109] Arnason et al. Identified that there the risk of lower extremity injury is approximately twice as higher when playing on turf compared to grass or gravel.[14]

Social Environment

Pressure from parents, teammates and coaches to do whatever it takes to win are examples of social pressures that may increase the risk of LE MSK injury. Athletes who feel immense pressure to win may begin taking bigger risks with the prospect of succeeding.[108] Taking bigger risks may result in making decisions that puts themselves in injurious situations. Parents' desire for their children to succeed may also result in them promoting sport specialization; parents may pressure their child into playing one sport, year round, to improve performance. This sports specialization may increase the risk of LE MSK injury.[110–115] Jayanthi et al. identified that risk of LE MSK injury is greater among highly specialized athletes compared to athletes with low specialization.[110] Sport specialization may increase the risk of injury because of the associated increased activity volume. Individuals who participate in organized athletics more than 8 months a year are at greater risk of injury.[110] Additionally, injury risk increases as weekly participation volume increases.[116]

INJURY RISK ASSESSMENT MODELS

Univariate Injury Prediction

Physical function characteristics are often studied as predictors of LE MSK injury. Most of these efforts, however, assess univariate prediction models focusing on factors such as LE ROM, LE postural control, LE power generation or LE neuromuscular control.[12,22,24–27,56,61]

Evidence for ankle dorsiflexion (DF) ROM as a predictor of injury is inconclusive.[12,46] Kaufman et al. identified reduced ankle DF ROM as a predictor of overuse MSK injury.[12] Beynnon et al. however, did not find an association between ankle DF and MSK injury.[46] Differences in studies designs, such as study population and injury definition, may contribute to differences in findings and therefore the role of DF ROM as an injury risk factor is unclear.

Postural control performance, as measured by the Lower Quarter Y-Balance Test, has been used to predict LE MSK injury in various studies.[56] Poor composite scores may increase the risk for injury.[17] Asymmetry greater than 4 cm in the anterior direction of the Lower Quarter Y-Balance Test may also increase the risk of injury.[17,21] Although Y-Balance test performance may indicate an increased risk of injury, the ability of the test to accurately predict injury occurrence at an individual level is unclear.

The anterior, single leg hop for distance (SLHOP) test is an assessment of power generation and controlled absorption that is believed to be a predictor of LE MSK injury. Research on this test as a predictor of injury is lacking but one study identified a relationship between SLHOP performance and injury risk.[22] Brumitt et al. identified that females with greater than a 10% asymmetry were at an increased risk of foot and ankle injury.[22] Although SLHOP performance may indicate an increased risk of injury, the ability of the test to predict injury occurrence is unclear.

The Landing Error Scoring System (LESS) is an assessment of neuromuscular control that has been studied as a predictor of LE MSK injury.[24,27,117] Research findings are mixed with some studies indicating potential to predict injury risk while others have found no such relationship.[24,27] Similar to the LESS, knee abduction moment during a drop vertical jump (DVJ) task may identify individuals at greater risk of ACL injury. Hewett et al identified greater risk in individuals who experience external knee abduction moments greater than 25 Nm during a DVJ task.[26] However, the true relationship between knee abduction moments and ACL injury is also unclear.[25]

Multivariate Injury Prediction

Although most research examines univariate predictors, some studies have developed multivariate prediction models.[19,21,23,118] Lehr et al developed a comprehensive screen including the Functional Movement Screen, Lower Quarter Y-Balance and vertical jump tests.[21] The model was predictive of injury risk, though not injury itself. Despite its promise, it was time intensive, taking 45-60 minutes per person.[21,119] The time demands make it unrealistic for large screenings.

Meyer et al. developed a multivariate prediction model by creating a nomogram to identify ACL injury risk in female athletes.[118] The nomogram included multiple factors such as demographics and anthropometric measurements.[118,120] This nomogram can only predict knee abduction moments however, and therefore may or may not be a valid predictor of ACL injury itself.[120] The same nomogram was used in an attempt to predict risk of patellofemoral pain syndrome (PFPS) since high abduction moments may also increase risk of PFPS.[121] As is the case with predicting ACL injury however, the value of the nomogram at predicting PFPS risk specifically is unclear.

Predictive Validity

Despite the breadth of literature on LE MSK injury risk assessment, predictive validity of risk assessments is generally poor.[28,29] Many predictors demonstrate an acceptable ability to identify greater injury risk, as assessed via odds ratios or relative risk ratios; however, there are no prediction models to date that demonstrate acceptable predictive statistics such as positive and negative likelihood ratios, as well as area under the curve statistics (i.e. C statistics).[17,19,22] This lack of acceptable predictive validity supports the need for a thorough understanding of injury risk to inform injury prediction efforts.

PATH ANALYSIS

Incorporation of path analysis frameworks may improve upon past injury risk assessment models. Analyzing effects of mediators and moderators on LE MSK injury risk may be of particular benefit. Mediation analysis is a path analysis method that allows for the estimation of direct and indirect effects of one variable on another.[122] Moderation analysis allows researchers to understand how the strength or direction of a proposed relationship varies based on the state of another variable.[122–124]

Mediation

As previously stated, mediation analysis allows researchers to understand how a particular variable may directly and indirectly influence an outcome of interest.[122] In such an analysis indirect effects are assessed as the effect of the predictor variable on the outcome variable through the predictor variable's effect on an intermediate variable (i.e. the mediator). The indirect effect is estimated as the product of the effect of the focal predictor on the mediator (i.e. coefficient for the focal predictor in path a) and the effect of the mediator on the outcome (i.e. coefficient of the mediator in path b).[125] A graphical depiction of a mediated effect can be found in Figure 1.

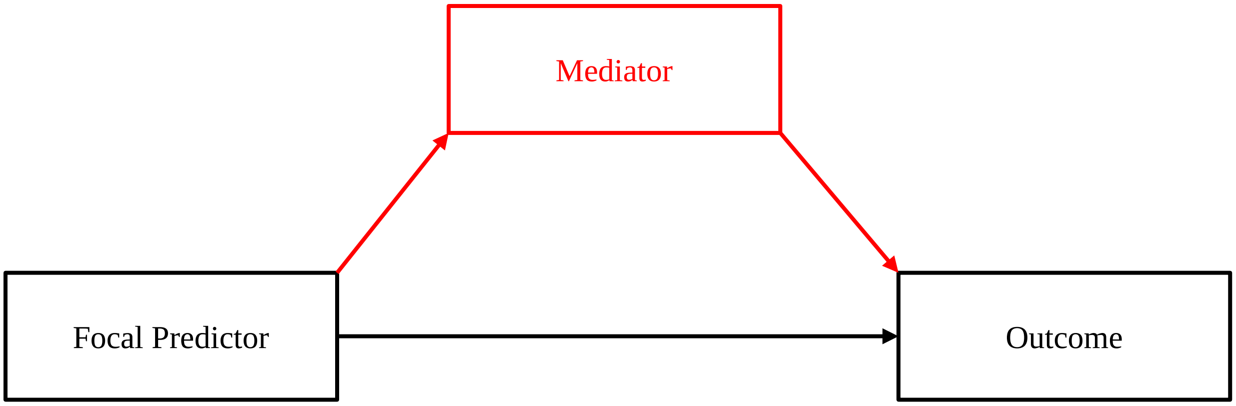


Figure 1. Graphical depiction of a mediated relationship. The effect of the focal predictor on the outcome occurs directly and indirectly (highlighted in red). The indirect effect occurs through its effect on the mediator, which in turn effects the outcome.

Researchers to date have not examined the role of mediators in LE MSK injury risk assessment. However, relationships among various functional performance characteristics support evaluating functional characteristics as mediators of injury risk. Understanding influences of ROM on postural control and power generation, as well as the influence of postural control on power generation, may help establish a theoretical path analytic framework.

The effect of ankle DF ROM on LE MSK injury risk may be mediated by LE postural control.[126–128] Mecagni et al. identified a relationship between ankle ROM and postural control with correlations ranging from 0.29 to 0.63.[127] Additionally, Hoch et al. identified that applying joint mobilizations to improve ankle dorsiflexion ROM also improved LE postural control.[128] It is important to acknowledge however that improvements in postural control following ankle mobilizations may occur through a different pathway than improved ROM. Both of these findings indicate the potential for a positive relationship between ankle ROM and postural control.

The effect of ankle DF ROM on LE MSK injury risk may be mediated by LE power generation and acceptance. Sufficient amounts of ankle DF ROM are required to perform the single leg hop for distance test, an assessment of LE power generation, and may be especially important when in a fatigued state.[129,130] Augustsson et al. identified that individuals in a fatigued state adopt a knee and ankle dominant strategy for generating power during a single leg hop task.[130]

LE power generation during a single leg hop test may mediate the effect of postural control on LE MSK injury risk. Improvements in postural control following balance training may improve power generation capabilities in older populations.[131] Additionally, postural orientation, a factor contributing to postural control, may be related to hop performance.[132] Trulsson et al. identified moderate, negative correlations between postural orientation and hop performance, indicating that worse postural orientation was associated with worse hop performance.[132]

The use of path analyses, specifically mediation analyses, to help understand the complex nature of injury is supported by research examining psychosocial predictors of injury. Researchers have established that negative-life-event stress does not alter injury frequency directly but instead indirectly.[133] Negative-life-event stress increases daily hassle which in turn increases injury frequency.[133] These findings, in addition to relationships among functional performance characteristics, support the use of mediation analyses in LE MSK injury risk assessment.

Moderation

Moderation occurs when the effect of one variable on an outcome depends on the state of another variable. That is, the effect of one variable on another is moderated by the additional variable. A graphical depiction of a moderated relationship can be found in Figure 2. Such an analysis results in the estimation of conditional effects.[122] Conditional effects represent the effect of one variable on another, for a specified value of the moderator. Moderation analyses allow researchers to establish relationships that may be present under certain conditions but not others. As with mediation analyses, moderation analyses are used frequently in psychology and social sciences.

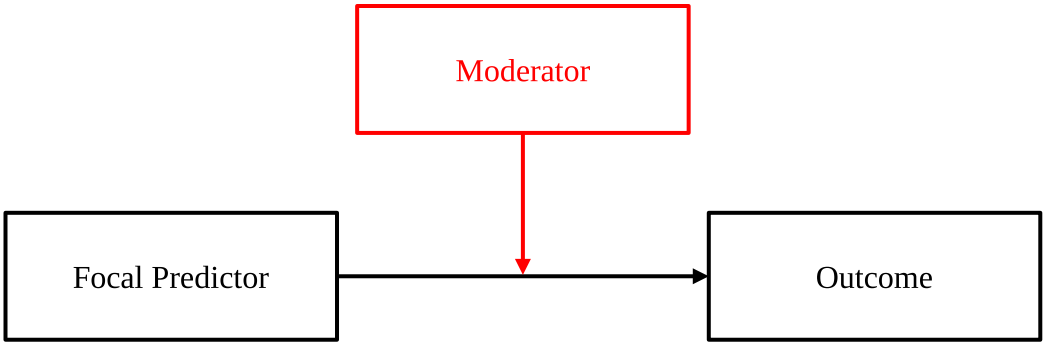


Figure 2. Graphical depiction of a moderated relationship. The effect of the focal predictor on the outcome varies as a function of the moderator (highlighted in red).

Although there is no current published research that uses this method to assess relationships between physical performance metrics and injury risk, researchers have examined relationships between psychosocial factors and injury.[134–137] Smith et al. identified that the relationship between life stress and adolescent sport injuries is potentially moderated by social support and coping skills.[135] Negative life stress events only increase the risk of injury for individuals with poor social support and poor coping skills.[135]

RESEARCH PROGRAM

Despite the breadth of research on injury risk identification[10,16,19,21,22,24,26,30,61,85,91,138,139], current injury risk assessment models are inadequate and no gold standard exists for effectively identifying risk of injury in physically active populations.[28,29] This gap in knowledge may result from a lack of understanding of how functional performance alters injury risk through direct, indirect and moderated effects. Therefore, the objective of this project is to assess the complex multifactorial nature of LE MSK injury risk in adolescent athletes. To achieve this objective we will: 1) describe the epidemiology of LE MSK injuries in high school soccer and basketball athletes; 2) identify direct and indirect effects of functional performance asymmetries on LE MSK injury in high school soccer and basketball athletes; and 3) determine if relationships between functional asymmetries and LE MSK injury risk are moderated by functional performances in high school soccer and basketball athletes. Achieving these objectives may result in a more accurate understanding of injury risk that will better inform injury prediction methods and contribute to the ultimate goal of injury prevention.

Chapter 3: Epidemiology of Lower Extremity Musculoskeletal Injury in US High School Boys' and Girls' Soccer and Basketball

ABSTRACT

Background: Athletic participation comes an inherent risk of lower extremity (LE) musculoskeletal (MSK) injury. Effectively reducing the risk of LE MSK injury in soccer and basketball may require sport-specific interventions, but minimal research has compared distributions and patterns of injury between the two sports.

Purpose: Describe the epidemiology of LE MSK injuries in high school soccer and basketball athletes.

Methods: Data from the 2012/2013 to 2015/2016 academic years were collected from High School Reporting Information Online (HS-RIO). Certified athletic trainers (ATs) from participating high schools reported injury incidence and athlete exposures (AE). An injury was defined as an event causing an athlete to seek care from an AT or physician and resulted in them missing at least one school-sanctioned practice or competition. An AE was defined as one athlete's participation in one school-sanctioned practice or competition. Injury rates per 1000AE were calculated overall, as well as by event type. Injury proportions were calculated to assess the distribution of injuries by body part, specific diagnosis, injury mechanism, and time loss. Injury rate ratios (IRR) and injury proportion ratios (IPR) with 95% confidence intervals (CI) were calculated to compare the relative differences between sports within sexes. Injury rate ratios and IPRs with 95%CI that didn't include "1.00" were considered statistically significant.

Results: The total injury rate was higher in boys' soccer than boys' basketball (IRR = 1.15, 95%CI = 1.03, 1.27) and higher in girls' soccer than girls' basketball (IRR = 1.31, 95%CI = 1.19, 1.44). The most common injuries in soccer and basketball, for both sexes, were sprains and strains; most injuries affected the ankle and knee. The proportion of injuries affecting the hip (boys: IPR = 3.37, 95%CI = 2.10, 5.40; girls: IPR = 1.74, 95%CI = 1.06, 2.88) or thigh/upper leg (boys: IPR = 3.24, 95%CI = 2.35, 4.48; girls: IPR = 1.97, 95%CI = 1.44, 2.70) was greater in soccer than basketball, regardless of sex. Injuries were most commonly caused by player contact or noncontact mechanisms, regardless of sport or sex.

Conclusion: The most common injuries were similar between sports suggesting both sports should emphasize preventing sprains and strains affecting the ankle and knee, specifically those resulting from player contact and noncontact mechanisms. Additional efforts are also needed to prevent hip and thigh/upper leg injuries in soccer.

INTRODUCTION

Over 7.8 million adolescents participate in high school athletics annually, with soccer and basketball being two of the most popular sports.[140] During the 2015-2016 academic year 975,808 basketball and 821,851 soccer athletes participated from 36,178 National Federation of State High School Associations (NFHS) sanctioned basketball teams and 23,730 NFHS sanctioned soccer teams.[140] Although athletic participation is associated with physical,[141] social,[141] and academic benefits,[141] it does not come without risks, specifically risk of lower extremity (LE) musculoskeletal (MSK) injury.[2,47,142] The overall rate of MSK injury in high school athletics has been reported to be 2.51 injuries per 1,000 athlete exposures (AE)[2] with a reported competition injury rate of 4.63/1000AE and a practice injury rate of 1.69/1000AE.[2] Over half (57.2%) of these injuries affect the LE.[2]

The large number of injuries that occur in this population result in not only short-term pain and dysfunction but also long-term consequences.[3,143–145] Knee injuries increase the risk of developing premature knee osteoarthritis in a variety of active populations.[146–149] Additionally, lateral ankle sprains increase the risk of developing chronic ankle instability (CAI).[150,151] Long-term consequences of LE MSK injury can lead to prolonged disability and decreased quality of life.[143,144,152] Effectively reducing the risk of LE MSK injury in soccer and basketball may require sport-specific interventions, and while previous studies have reported rates, distributions, and patterns of injury for basketball and soccer individually they have not often explicitly compared the two.[2,88,89] As a result there is a need for a singular study comparing epidemiological patterns of injuries between soccer and basketball. Understanding the varying rates and patterns of injury may help improve strategies to prevent LE MSK injury.

The purpose of this study was to describe the epidemiology of LE MSK injuries in high school soccer and basketball athletes during the 2012/2013 to 2015/2016 academic years. The specific aims were to compare between sports 1) injury rates overall and by event type; 2) proportions of injuries by body part; 3) proportions of injuries by specific diagnosis; 4) proportion of injuries by injury mechanism; 5) proportions of injuries by time loss.

METHODS

Injury Surveillance

Data from the 2012/2013 to 2015/2016 academic years were collected from the web-based national injury surveillance system High School Reporting Information Online (HS-RIO). HS-RIO was launched to capture injury and athlete exposure (AE) data on athletes from a representative national sample of U.S. high schools. HS-RIO data consisted of a random sample of 100 high schools that reported data for boys' and girls' soccer and basketball. High schools were recruited into eight strata based on school population (enrollment $\leq$ 1000, or $>$ 1000) and US Census geographic region. Previous publications have described the sampling and data collection of HS-RIO.[2,153]

Annually, certified athletic trainers (ATs) from participating high schools reported injury incidence and AE information weekly throughout the academic year using a secure website. An LE injury was defined as an event causing an athlete to seek care from an AT or physician and resulted in them missing at least one school-sanctioned practice or competition. As a result, only time-loss injuries are captured in this study. For each injury, the AT completed a detailed injury report on the injured athlete (age, height, weight, etc.), the injury (site, diagnosis, severity, etc.), and the injury event (activity, mechanism, etc.). Throughout each academic year, participating ATs were able to view and update previously submitted reports as needed with new information (e.g., time loss). If one injury event resulted in multiple injuries only the primary injury was captured. An AE was defined as one athlete's participation in one school-sanctioned practice or competition.

Statistical Analysis

National LE MSK injury count estimates were calculated by applying a weighting algorithm based on the inverse probability of participant schools' selection into the study (based on geographic location and high school size) to individual case counts. Injury rates per 1000AE were calculated based on unweighted injury counts and AE, including overall injury rates, and rates by event type (i.e. practice or competition). Injury proportions were calculated by body part (i.e. foot, ankle, lower leg, knee, thigh, hip), specific diagnosis (i.e. sprain, strain, contusion, fracture), injury mechanism (i.e. noncontact, contact with another player, other contact, overuse/chronic) and time loss (i.e. < 1 week, 1-3 weeks, more than 3 weeks, season/career ending). Injury rate ratios (IRR) with 95% confidence intervals (CI) were calculated to compare the relative differences between sports within sexes (i.e. boys' basketball vs. boys' soccer, girls' basketball vs. girls' soccer). The following is an example of an IRR comparing overall injury rates between boys' basketball and boys' soccer:

$$\text{IRR} = \frac{\left(\frac{\text{No. of injuries in boys' basketball}}{\text{No. of athlete exposures in boys' basketball}}\right)}{\left(\frac{\text{No. of injuries in boys' soccer}}{\text{No. of athlete exposures in boys' soccer}}\right)}$$

Injury proportion ratios (IPR) with 95%CI compared injury proportions between sports within sexes. The following is an example of an IPR comparing the proportion of all injuries that affected the knee between girls' basketball and girls' soccer:

$$\text{IPR} = \frac{\left(\frac{\text{No. of girls' basketball injuries affecting the knee}}{\text{Total no. of girls' basketball injuries}}\right)}{\left(\frac{\text{No. of girls' soccer injuries affecting the knee}}{\text{Total no. of girls' soccer injuries}}\right)}$$

Injury rate ratios and IPRs with 95%CI that didn't include "1.00" were considered statistically significant.

RESULTS

Injury Frequencies and Rates

Boys' Sports

Between 2012/2013 and 2015/2016, a total of 1,423 injuries were reported in boys' high school soccer and basketball, equating to a national estimate of 565,885 injuries. (Table 1). The total injury rates in boys' soccer and basketball were 0.99/1000AE (95%CI = 0.92, 1.07) and 0.87/1000AE (95%CI = 0.81, 0.93), respectively.

The total injury rate was higher in boys' soccer than boys' basketball (IRR = 1.15, 95%CI = 1.03, 1.27). Competition injury rates were also greater in boys' soccer (IRR = 1.35, 95%CI = 1.17, 1.55). No differences in practice injury rates between sports were observed (IRR = 0.94, 95%CI = 0.80, 1.10).

Table 1. Injury rates by event type in boys' soccer and basketball

	Event type	# injuries in sample	National estimate	AE	Injury rate per 1000 AE (95%CI)	Injury rate ratio (95%CI)[a]
Overall						
	Competition	772	312,710	471,703	1.64 (1.52, 1.75)	2.70 (2.43 , 2.99)[b]
	Practice	651	253,175	1,072,865	0.61 (0.56, 0.65)	
	Total	1423	565,885	1,544,568	0.92 (0.87, 0.97)	
Soccer						
	Competition	393	218,064	205,250	1.91 (1.73, 2.1)[c]	3.27 (2.80 , 3.82)[b]
	Practice	272	157,287	464,804	0.59 (0.52, 0.65)	
	Total	665	375,351	670,054	0.99 (0.92, 1.07)[c]	
Basketball						
	Competition	379	94,646	266,453	1.42 (1.28, 1.57)	2.28 (1.98 , 2.63)[b]
	Practice	379	95,888	608,061	0.62 (0.56, 0.69)	
	Total	758	190,534	874,514	0.87 (0.81, 0.93)	

Note: AE=Athlete-exposure; CI=Confidence interval

[a]Injury rate ratio is competition injury rate:practice injury rate

[b]Competition injury rate is significantly different than practice injury rate (IRR ≠ 1.00)

[c]Injury rate for boys' soccer differs significantly from boys' basketball (IRR ≠ 1.00)

Girls' Sports

During this same time period, a total of 1,671 injuries were reported in girls' high school soccer and basketball, equating to a national estimate of 727,763 injuries (Table 2). The total injury rates in girls' soccer and basketball were 1.50/1000AE (95%CI = 1.40, 1.60) and 1.14/1000AE (95%CI = 1.06, 1.22), respectively. The total injury rate was higher in girls' soccer than girls' basketball (IRR = 1.31, 95%CI = 1.19, 1.44). Competition injury rates were also greater in girls' soccer (IRR = 1.66, 95%CI = 1.46, 1.88). No differences in practice injury rates were noted between sports (IRR = 0.95, 95%CI = 0.81, 1.10).

Table 2. Injury rates by event type in girls' soccer and basketball

	Event type	# injuries in sample	National estimate	AE	Injury rate per 1000 AE (95%CI)	Injury rate ratio (95%CI)[a]
Overall						
	Competition	990	456,120	391,525	2.53 (2.37, 2.69)	3.28 (2.98 , 3.62)[b]
	Practice	681	271,643	883,654	0.77 (0.71, 0.83)	
	Total	1671	727,763	1,275,179	1.31 (1.25, 1.37)	
Soccer						
	Competition	589	351,040	183,783	3.20 (2.95, 3.46)[c]	4.28 (3.73 , 4.91)[b]
	Practice	313	171,847	418,094	0.75 (0.67, 0.83)	
	Total	902	522,887	601,877	1.50 (1.40, 1.60)[c]	
Basketball						
	Competition	401	105,080	207,742	1.93 (1.74, 2.12)	2.44 (2.12 , 2.81)[b]
	Practice	368	99,796	465,560	0.79 (0.71, 0.87)	
	Total	769	204,876	673,302	1.14 (1.06, 1.22)	

Note: AE=Athlete-exposure; CI=Confidence interval

[a]Injury rate ratio is competition injury rate:practice injury rate

[b]Competition injury rate is significantly different than practice injury rate (IRR ≠ 1.00)

[c]Injury rate for girls’ soccer differs significantly from girls’ basketball (IRR ≠ 1.00)

Competition Level

Injury rates were greater in competition than practice regardless of sport or sex. Competition injury rates were 3.27 (95%CI = 2.80, 3.82) and 2.28 (95%CI = 1.98, 2.63) times greater than practice injury rates for boys' soccer and boys' basketball, respectively (Table 1). Competition injury rates were 4.28 (95%CI = 3.73, 4.91) and 2.44 (95%CI = 2.12, 2.81) times greater than practice injury rates for girls' soccer and girls' basketball, respectively (Table 2).

Injured Body Part

Boys' Sports

The most commonly injured body parts regardless of sport were the ankle (soccer = 26.47%, basketball = 55.94%) and knee (soccer = 24.06%, basketball = 22.56%) (Table 3). The third most commonly injured body part in soccer and basketball was the thigh/upper leg (19.25%) and foot (7.78%), respectively. The proportion of injuries affecting the hip was greater in boys' soccer than boys' basketball (IPR = 3.37, 95%CI = 2.10, 5.40). The same was true of the thigh/upper leg (IPR = 3.24, 95%CI = 2.35, 4.48) and lower leg (IPR = 2.37, 95%CI = 1.63, 3.46). The proportion of injuries affecting the ankle was lower in boys' soccer than boys' basketball (IPR = 0.47, 95%CI = 0.41, 0.55).

Table 3. Injury rates and proportions by body part in boys' soccer and basketball

	Body part	# injuries in sample	Injury rate per 1000 AE (95%CI)	Injury proportion (95%CI)
Overall				
	Hip	87	0.06 (0.04, 0.07)	6.11 (4.83, 7.4)
	Thigh/upper leg	173	0.11 (0.1, 0.13)	12.16 (10.35, 13.97)
	Knee	331	0.21 (0.19, 0.24)	23.26 (20.75, 25.77)
	Lower leg	114	0.07 (0.06, 0.09)	8.01 (6.54, 9.48)
	Ankle	600	0.39 (0.36, 0.42)	42.16 (38.79, 45.54)
	Foot	118	0.08 (0.06, 0.09)	8.29 (6.8, 9.79)
Soccer				
	Hip	65	0.1 (0.07, 0.12)	9.77 (7.4, 12.15)[a]
	Thigh/upper leg	128	0.19 (0.16, 0.22)	19.25 (15.91, 22.58)[a]
	Knee	160	0.24 (0.2, 0.28)	24.06 (20.33, 27.79)
	Lower leg	77	0.11 (0.09, 0.14)	11.58 (8.99, 14.17)[a]
	Ankle	176	0.26 (0.22, 0.3)	26.47 (22.56, 30.38)[a]
	Foot	59	0.09 (0.07, 0.11)	8.87 (6.61, 11.14)
Basketball				
	Hip	22	0.03 (0.01, 0.04)	2.9 (1.69, 4.12)
	Thigh/upper leg	45	0.05 (0.04, 0.07)	5.94 (4.2, 7.67)
	Knee	171	0.2 (0.17, 0.22)	22.56 (19.18, 25.94)
	Lower leg	37	0.04 (0.03, 0.06)	4.88 (3.31, 6.45)
	Ankle	424	0.48 (0.44, 0.53)	55.94 (50.61, 61.26)
	Foot	59	0.07 (0.05, 0.08)	7.78 (5.8, 9.77)

Note: AE=Athlete-exposure; CI=Confidence interval

[a]Injury proportion is significantly different than basketball (IPR $\neq$ 1.00)

Girls' Sports

The most commonly injured body parts regardless of sport were the ankle (soccer = 35.03%, basketball = 47.20%), knee (soccer = 29.38%, basketball = 32.64%), and thigh/upper leg (soccer = 13.08%, basketball = 6.63%) (Table 4). The proportion of injuries affecting the hip was greater in girls' soccer than girls' basketball (IPR = 1.74, 95%CI = 1.06, 2.88). The same was true of the thigh/upper leg (IPR = 1.97, 95%CI = 1.44, 2.70) and foot (IPR = 2.05, 95%CI = 1.40, 3.00). The proportion of injuries affecting the ankle was lower in girls' soccer than girls' basketball (IPR = 0.74, 95%CI = 0.66, 0.83).

Table 4. Injury rates and proportions by body part in girls' soccer and basketball

	Body part	# injuries in sample	Injury rate per 1000 AE (95%CI)	Injury proportion (95%CI)
Overall				
	Hip	67	0.05 (0.04, 0.07)	4.01 (3.05, 4.97)
	Thigh/upper leg	169	0.13 (0.11, 0.15)	10.11 (8.59, 11.64)
	Knee	516	0.4 (0.37, 0.44)	30.88 (28.22, 33.54)
	Lower leg	121	0.09 (0.08, 0.11)	7.24 (5.95, 8.53)
	Ankle	679	0.53 (0.49, 0.57)	40.63 (37.58, 43.69)
	Foot	119	0.09 (0.08, 0.11)	7.12 (5.84, 8.4)
Soccer				
	Hip	45	0.07 (0.05, 0.1)	4.99 (3.53, 6.45)[a]
	Thigh/upper leg	118	0.2 (0.16, 0.23)	13.08 (10.72, 15.44)[a]
	Knee	265	0.44 (0.39, 0.49)	29.38 (25.84, 32.92)
	Lower leg	74	0.12 (0.09, 0.15)	8.2 (6.33, 10.07)
	Ankle	316	0.53 (0.47, 0.58)	35.03 (31.17, 38.9)[a]
	Foot	84	0.14 (0.11, 0.17)	9.31 (7.32, 11.3)[a]
Basketball				
	Hip	22	0.03 (0.02, 0.05)	2.86 (1.67, 4.06)
	Thigh/upper leg	51	0.08 (0.05, 0.1)	6.63 (4.81, 8.45)
	Knee	251	0.37 (0.33, 0.42)	32.64 (28.6, 36.68)
	Lower leg	47	0.07 (0.05, 0.09)	6.11 (4.36, 7.86)
	Ankle	363	0.54 (0.48, 0.59)	47.2 (42.35, 52.06)
	Foot	35	0.05 (0.03, 0.07)	4.55 (3.04, 6.06)

Note: AE=Athlete-exposure; CI=Confidence interval

[a]Injury proportion is significantly different than basketball (IPR $\neq$ 1.00)

Injury Mechanism

Boys' Sports

The most common injury mechanisms regardless of sport were contact with another player (soccer = 42.71%, basketball = 36.81%) and noncontact (soccer = 33.98%, basketball = 34.17%) (Table 5). The proportion of injuries resulting from contact with another player was greater in soccer than basketball (IPR = 1.16, 95%CI = 1.02, 1.32). The same was true of overuse/chronic injuries (IPR = 1.42, 95%CI = 1.00, 2.02). The proportion of injuries resulting from contact with something other than another player (e.g. contact with the playing surface) was lower in soccer than basketball (IPR = 0.57, 95%CI = 0.45, 0.74).

Table 5. Injury rates and proportions by injury mechanisms in boys' soccer and basketball

	Injury mechanism	# injuries in sample	Injury rate per 1000 AE (95%CI)	Injury proportion (95%CI)
Overall				
	Noncontact	485	0.31 (0.29, 0.34)	34.08 (31.05, 37.12)
	Contact with another player	563	0.36 (0.33, 0.39)	39.56 (36.3, 42.83)
	Other contact	230	0.15 (0.13, 0.17)	16.16 (14.07, 18.25)
	Overuse/chronic	117	0.08 (0.06, 0.09)	8.22 (6.73, 9.71)
Soccer				
	Noncontact	226	0.34 (0.29, 0.38)	33.98 (29.55, 38.42)
	Contact with another player	284	0.42 (0.37, 0.47)	42.71 (37.74, 47.67)[a]
	Other contact	77	0.11 (0.09, 0.14)	11.58 (8.99, 14.17)[a]
	Overuse/chronic	65	0.1 (0.07, 0.12)	9.77 (7.4, 12.15)[a]
Basketball				
	Noncontact	259	0.3 (0.26, 0.33)	34.17 (30.01, 38.33)
	Contact with another player	279	0.32 (0.28, 0.36)	36.81 (32.49, 41.13)
	Other contact	153	0.17 (0.15, 0.2)	20.18 (16.99, 23.38)
	Overuse/chronic	52	0.06 (0.04, 0.08)	6.86 (5, 8.72)

Note: AE=Athlete-exposure; CI=Confidence interval

[a]Injury proportion is significantly different than basketball (IPR ≠ 1.00)

Girls' Sports

The most common injury mechanisms regardless of sport were contact with another player (soccer = 40.80%, basketball = 27.70%) and noncontact (soccer = 34.15%, basketball = 41.35%) (Table 6). The proportion of injuries resulting from contact with another player was greater in soccer than basketball (IPR = 1.47, 95%CI = 1.28, 1.69). The proportion of injuries resulting from noncontact was lower in soccer than basketball (IPR = 0.83, 95%CI = 0.73, 0.93).

Table 6. Injury rates and proportions by injury mechanism in girls' soccer and basketball

	Injury mechanism	# injuries in sample	Injury rate per 1000 AE (95%CI)	Injury proportion (95%CI)
Overall				
	Noncontact	626	0.49 (0.45, 0.53)	37.46 (34.53, 40.4)
	Contact with another player	581	0.46 (0.42, 0.49)	34.77 (31.94, 37.6)
	Other contact	258	0.2 (0.18, 0.23)	15.44 (13.56, 17.32)
	Overuse/chronic	158	0.12 (0.1, 0.14)	9.46 (7.98, 10.93)
Soccer				
	Noncontact	308	0.51 (0.45, 0.57)	34.15 (30.33, 37.96)[a]
	Contact with another player	368	0.61 (0.55, 0.67)	40.8 (36.63, 44.97)[a]
	Other contact	129	0.21 (0.18, 0.25)	14.3 (11.83, 16.77)
	Overuse/chronic	82	0.14 (0.11, 0.17)	9.09 (7.12, 11.06)
Basketball				
	Noncontact	318	0.47 (0.42, 0.52)	41.35 (36.81, 45.9)
	Contact with another player	213	0.32 (0.27, 0.36)	27.7 (23.98, 31.42)
	Other contact	129	0.19 (0.16, 0.22)	16.78 (13.88, 19.67)
	Overuse/chronic	76	0.11 (0.09, 0.14)	9.88 (7.66, 12.1)

Note: AE=Athlete-exposure; CI=Confidence interval

[a]Injury proportion is significantly different than basketball (IPR $\neq$ 1.00)

Specific Diagnosis

Boys' Sports

The most common injury diagnoses regardless of sport were sprains (soccer = 35.34%, basketball = 64.25%) and strains (soccer = 27.22%, basketball = 9.63%) (Table 7). Soccer had a larger proportion of injuries diagnosed as strains (IPR = 2.83, 95%CI = 2.20, 3.63) and contusions (IPR = 2.11, 95%CI = 1.57, 2.84) than basketball. A smaller proportion of soccer injuries were diagnosed as sprains compared to basketball (IPR = 0.55, 95%CI = 0.49, 0.62).

Table 7. Injury rates and proportions by specific diagnosis in boys' soccer and basketball

	Specific diagnosis	# injuries in sample	Injury rate per 1000 AE (95%CI)	Injury proportion (95%CI)
Overall				
	Sprain	722	0.47 (0.43, 0.5)	50.74 (47.04, 54.44)
	Strain	254	0.16 (0.14, 0.18)	17.85 (15.65, 20.04)
	Fracture	83	0.05 (0.04, 0.07)	5.83 (4.58, 7.09)
	Contusion	171	0.11 (0.09, 0.13)	12.02 (10.22, 13.82)
Soccer				
	Sprain	235	0.35 (0.31, 0.4)	35.34 (30.82, 39.86)[a]
	Strain	181	0.27 (0.23, 0.31)	27.22 (23.25, 31.18)[a]
	Fracture	39	0.06 (0.04, 0.08)	5.86 (4.02, 7.71)
	Contusion	111	0.17 (0.13, 0.2)	16.69 (13.59, 19.8)[a]
Basketball				
	Sprain	487	0.56 (0.51, 0.61)	64.25 (58.54, 69.95)
	Strain	73	0.08 (0.06, 0.1)	9.63 (7.42, 11.84)
	Fracture	44	0.05 (0.04, 0.07)	5.8 (4.09, 7.52)
	Contusion	60	0.07 (0.05, 0.09)	7.92 (5.91, 9.92)

Note: AE=Athlete-exposure; CI=Confidence interval

[a]Injury proportion is significantly different than basketball (IPR $\neq$ 1.00)

Girls' Sports

The most common injury diagnoses regardless of sport were sprains (soccer = 51.44%, basketball = 59.69%) and strains (soccer = 17.52%, basketball = 14.17%) (Table 8). A larger proportion of soccer injuries were diagnosed as fractures (IPR = 1.84, 95%CI = 1.16, 2.93) and contusions (IPR = 2.15, 95%CI = 1.53, 3.04) compared to basketball. Soccer had a smaller proportion of injuries diagnosed as sprains than basketball (IPR = 0.86, 95%CI = 0.79, 0.94).

Table 8. Injury rates and proportions by specific diagnosis in girls' soccer and basketball

	Specific diagnosis	# injuries in sample	Injury rate per 1000 AE (95%CI)	Injury proportion (95%CI)
Overall				
	Sprain	923	0.72 (0.68, 0.77)	55.24 (51.67, 58.8)
	Strain	267	0.21 (0.18, 0.23)	15.98 (14.06, 17.9)
	Fracture	79	0.06 (0.05, 0.08)	4.73 (3.69, 5.77)
	Contusion	148	0.12 (0.1, 0.13)	8.86 (7.43, 10.28)
Soccer				
	Sprain	464	0.77 (0.7, 0.84)	51.44 (46.76, 56.12)[a]
	Strain	158	0.26 (0.22, 0.3)	17.52 (14.79, 20.25)
	Fracture	54	0.09 (0.07, 0.11)	5.99 (4.39, 7.58)[a]
	Contusion	106	0.18 (0.14, 0.21)	11.75 (9.51, 13.99)[a]
Basketball				
	Sprain	459	0.68 (0.62, 0.74)	59.69 (54.23, 65.15)
	Strain	109	0.16 (0.13, 0.19)	14.17 (11.51, 16.84)
	Fracture	25	0.04 (0.02, 0.05)	3.25 (1.98, 4.53)
	Contusion	42	0.06 (0.04, 0.08)	5.46 (3.81, 7.11)

Note: AE=Athlete-exposure; CI=Confidence interval

[a]Injury proportion is significantly different than basketball (IPR $\neq$ 1.00)

Time Loss

Proportions of injuries by time loss for boys' and girls' sports are reported in Tables 9 and 10, respectively. Injuries resulting in less than 1 week of time lost from participation accounted for the largest proportion of injuries in boys' sports (soccer = 44.36%, basketball = 41.29%), followed by 1-3 weeks lost from participation (soccer = 30.83%, basketball = 31.66%). The same finding occurred in girls' sports where injuries resulting in less than 1 week of time lost from participation accounted for the largest proportion of injuries (soccer = 36.25%, basketball = 39.79%), followed by 1-3 weeks lost from participation (soccer = 32.04%, basketball = 28.22%).

Table 9. Injury rates and proportions by time loss in boys' soccer and basketball

	Time loss	# injuries in sample	Injury rate per 1000 AE (95%CI)	Injury proportion (95%CI)
Overall				
	< 1 week	608	0.39 (0.36, 0.42)	42.73 (39.33, 46.12)
	1-3 weeks	445	0.29 (0.26, 0.31)	31.27 (28.37, 34.18)
	> 3 weeks	103	0.07 (0.05, 0.08)	7.24 (5.84, 8.64)
	Season ending	60	0.04 (0.03, 0.05)	4.22 (3.15, 5.28)
Soccer				
	< 1 week	295	0.44 (0.39, 0.49)	44.36 (39.3, 49.42)
	1-3 weeks	205	0.31 (0.26, 0.35)	30.83 (26.61, 35.05)
	> 3 weeks	48	0.07 (0.05, 0.09)	7.22 (5.18, 9.26)
	Season ending	28	0.04 (0.03, 0.06)	4.21 (2.65, 5.77)
Basketball				
	< 1 week	313	0.36 (0.32, 0.4)	41.29 (36.72, 45.87)
	1-3 weeks	240	0.27 (0.24, 0.31)	31.66 (27.66, 35.67)
	> 3 weeks	55	0.06 (0.05, 0.08)	7.26 (5.34, 9.17)
	Season ending	32	0.04 (0.02, 0.05)	4.22 (2.76, 5.68)

Note: AE=Athlete-exposure; CI=Confidence interval

Table 10. Injury rates and proportions by time loss in girls' soccer and basketball

	Time loss	# injuries in sample	Injury rate per 1000 AE (95%CI)	Injury proportion (95%CI)
Overall				
	< 1 week	633	0.5 (0.46, 0.54)	37.88 (34.93, 40.83)
	1-3 weeks	506	0.4 (0.36, 0.43)	30.28 (27.64, 32.92)
	> 3 weeks	91	0.07 (0.06, 0.09)	5.45 (4.33, 6.56)
	Season ending	136	0.11 (0.09, 0.12)	8.14 (6.77, 9.51)
Soccer				
	< 1 week	327	0.54 (0.48, 0.6)	36.25 (32.32, 40.18)
	1-3 weeks	289	0.48 (0.42, 0.54)	32.04 (28.35, 35.73)
	> 3 weeks	44	0.07 (0.05, 0.09)	4.88 (3.44, 6.32)
	Season ending	79	0.13 (0.1, 0.16)	8.76 (6.83, 10.69)
Basketball				
	< 1 week	306	0.45 (0.4, 0.51)	39.79 (35.33, 44.25)
	1-3 weeks	217	0.32 (0.28, 0.37)	28.22 (24.46, 31.97)
	> 3 weeks	47	0.07 (0.05, 0.09)	6.11 (4.36, 7.86)
	Season ending	57	0.08 (0.06, 0.11)	7.41 (5.49, 9.34)

Note: AE=Athlete-exposure; CI=Confidence interval

DISCUSSION

This study compared rates and distributions of LE MSK injuries between boys' and girls' soccer and basketball using a national injury surveillance system. The most important finding of this study was that injury rates were greater in soccer than basketball, and greater in competitions than practices, regardless of sex. The most common injuries were similar between the two sports suggesting both sports should emphasize preventing ankle and knee injuries; soccer may benefit from additional efforts to prevent hip and thigh/upper leg injuries. These findings may help inform the development of injury prevention programs for soccer and basketball athletes.

Injury Frequencies and Rates

The total injury rates in boys' soccer and basketball were 0.99/1000AE and 0.87/1000AE, respectively. The total injury rates in girls' soccer and basketball were 1.50/1000AE and 1.14/1000AE, respectively. These rates are lower than those previously reported by Borowski et al.[154] and Rechel et al.,[2] however the differences may be a result of study methodology. Borowski et al.[154] and Rechel et al.[2] evaluated injuries affected any body part whereas we only evaluated lower extremity injuries.

Lower extremity MSK injury rates were greater in soccer than basketball for both boys (IRR = 1.15, 95%CI = 1.03, 1.27) and girls (IRR = 1.31, 95%CI = 1.19, 1.44). The increased rate of injury may be a result of potentially greater velocities at which soccer players are moving. Soccer is played over a longer distance than basketball, potentially allowing players to reach greater velocities. These greater velocities may be accompanied by greater forces, increasing the risk of injury.

Injury rates were also greater in competitions than practice, regardless of sport or sex. This finding is consistent with previous research on high school,[2] college,[50,88,155] and professional athletes[156–158] and may indicate an increased intensity of play and risk taking during competitions compared to practices. An individual's willingness to take risks may increase if the perceived gain is meaningful enough[159] and since games can be won or lost the perceived gain of winning may be meaningful enough for athletes to take greater risks compared to practices. The increased willingness to take risks may result in more injuries during games compared to practices, particularly injuries resulting from player contact.

Injured Body Part

The ankle and knee were the most commonly injured body parts in both soccer and basketball, regardless of sex. These findings are consistent with previous research in high school and collegiate athletes.[2,88,154,155] Rechel et al. reported that 22.7% of high school sports injuries affect the ankle. Borowski et al. reported that 35.9% and 18.2% of high school girls' basketball injuries affect the ankle/foot and knee, respectively; 43.2% and 10.6% of high school boys' basketball injuries affect the ankle/foot and knee, respectively.[154] These findings are likely explained by sport demands. Cutting and jumping demands of these sports may predispose athletes to primarily ankle and knee injuries.

A larger percentage of injuries affected the hip and thigh/upper leg in soccer compared to basketball for both boys and girls. The increased proportion of injuries affecting these regions may reflect sport-specific demands. The high volume of kicking may place a greater strain on the hip/thigh musculature, resulting in more muscle strains. Additionally, soccer requires more running over the course of a game which may also place an athlete at greater risk of running-related thigh/upper leg strains, such as hamstring and quadriceps strains, as compared to basketball. The increased running demands may also account for the larger proportion of lower leg injuries in boys' soccer compared to basketball, particularly overuse leg injuries such as medial tibial stress syndrome. The proportion of injuries in our sample resulting from overuse/chronic mechanisms was greater in boys' soccer than basketball, further supporting this hypothesis. These findings highlight the need for soccer-specific injury prevention programs that include strategies for reducing hip, thigh/upper leg, and lower leg injuries.

A smaller proportion of injuries affected the ankle in soccer than basketball, regardless of sex. This is consistent with previous reports that ankle injury rates, as well as proportions of all injuries that affect ankle, are greater in basketball than soccer.[160] One possible explanation for this finding is that basketball is played in a smaller area which provides a greater risk of stepping on another player and suffering a lateral ankle sprain. McKay et al. reported that approximately 23% of ankle sprains in basketball result from landing on another player's foot.[67] Sharper lateral cutting maneuvers also occur more often in basketball than soccer, potentially increasing the risk of a noncontact lateral ankle sprain. McKay et al. reported that approximately 30% of ankle sprains in basketball result from sharp twists or turns.[67] These findings indicate that although strategies to prevent ankle sprains are necessary for both soccer and basketball athletes, they may be especially important in basketball.

Injury Mechanism

The primary mechanism of injury in boys' sports and girls' soccer, as well as boys' basketball, was contact with another player. This finding is consistent with previous research on severe injuries in high school athletes indicating that contact with another player accounts for the largest proportion of severe injuries in soccer (27.9%).[161] Player contact also accounts for the largest proportion of injuries in various college sports.[88] Given the large proportion of injuries resulting from player contact, additional emphasis on preventing contact injuries is needed. Programs such as the FIFA 11+[162,163] incorporate player contact but more emphasis on learning how to control and react to player contact may be needed. Preventing player contact injuries may also require greater enforcement of player contact rules. Enforcing such rules during rebounding in basketball and slide tackling in soccer may be particularly effective. Rule enforcement may be particularly important in soccer where the proportion of injuries resulting from contact with another player was greater than basketball for both sexes (boys: IPR = 1.16, 95%CI = 1.02, 1.32; girls: IPR = 1.47, 95%CI = 1.28, 1.69).

The primary mechanism of injury in girls' basketball was noncontact. This finding may reflect the relatively high risk of anterior cruciate ligament (ACL) injury among female basketball players.[89] Anterior cruciate ligament injuries account for approximately 35% of all knee injuries in high school girls' basketball.[89] Although both soccer and basketball would benefit from prevention programs designed to prevent noncontact injuries, such programs may be of additional benefit among girls' basketball players.

Specific Diagnosis

Sprains and strains were the most common injuries in boys' and girls' soccer and basketball. This finding is consistent with previous literature reporting that sprains and strains account for the largest proportion of injuries in high school athletes, approximately 40-70% of injuries in boys' and girls' soccer and basketball, respectively.[2] Specific proportions vary by sport, sex, and event type (i.e. competition or practice).[2]

A larger proportion of injuries in boys' soccer were classified as strains and contusions when compared to boys' basketball. As was hypothesized regarding the most commonly injured body parts, these findings may reflect sport-specific demands and tasks. The high volume of kicking and longer distance running in soccer may place a greater strain on the hip/thigh musculature, resulting in more muscle strains. Differences in proportions of contusions may be a result of slide tackling in soccer. Slide tackles often result in contact with the opposing player which may result in contusions. This might also explain this increased proportion of fractures and contusions in girls' soccer compared to girls' basketball.

Limitations

Since we only evaluated high school athletes our findings may not be generalizable to other playing levels, such as youth, college, or professional programs. We also cannot generalize our results to non-time loss injuries since we only included injuries that resulted in the loss of at least one school-sanctioned practice or competition. We calculated AE using number of competitions and practices instead of minutes or hours of exposure. Not all athletes will participate for the same amount of time and therefore calculating AE at the event level, as we did, does not capture variations in injury rates by participation time. Although all data came from high school athletes, there are skill level differences within high school athletes that we were unable to capture. As a result we are not able to examine variations in rates and distributions of injuries between various skill levels within high school athletics.

CONCLUSION

This study compared rates and distributions of LE MSK injuries between boys' and girls' soccer and basketball using a national injury surveillance system. Injury rates were greater in soccer than basketball, and greater in competitions than practices, regardless of sex. The most common injuries were similar between sports suggesting both sports should emphasize preventing sprains and strains affecting the ankle and knee, specifically those resulting from player contact and noncontact mechanisms. Additional efforts are also needed to prevent hip and thigh/upper leg injuries in soccer. These findings may help inform the development of sport-specific injury prevention programs for soccer and basketball athletes.

Chapter 4: Functional Asymmetries and Lower Extremity Injury: Direct and Indirect Effects

ABSTRACT

Background: Although athletic participation comes with many benefits, it also comes with an inherent risk of lower extremity (LE) musculoskeletal (MSK) injury. Methods for identifying individuals most likely to suffer injuries during sport participation have been studied in an attempt to intervene and reduce injury incidence but no gold standard for doing so has been established. This gap in knowledge may result from a focus on risk factors' direct effects on injury and a lack of understanding of their indirect effects.

Purpose: Identify direct and indirect effects of functional performance asymmetries, as well as drop landing technique, on odds of LE MSK injury in boys' and girls' high school soccer and basketball athletes.

Methods: Data for this study were prospectively collected among male and female athletes ages 13-19 on a high school sponsored soccer or basketball team. Prior to the start of their competitive sport season participants underwent four functional assessments consisting of ankle dorsiflexion (DF) range of motion (ROM) asymmetry, single leg anterior reach (SLAR) asymmetry, anterior single leg hop for distance (SLHOP) asymmetry, and Impression Landing Error Scoring System (iLESS) performance. Participant questionnaires also captured age, sex, sport, and injury history. LE MSK injury data were reported throughout each sport season by certified athletic trainers using the injury surveillance system High School Reporting Information Online. Linear and logistic regressions were used to assess whether any of the four functional performance variables were directly or indirectly related to LE MSK injury.

Results: 1,384 males (age=15.66±1.22 years, height=1.77±0.09 m, weight=68.97±13.15 kg) and 1,261 females (age=15.49±1.17 years, height=1.65±0.07 m, weight=60.54±10.12 kg) participated in this prospective study. Only injury history was significantly related to odds of future LE MSK injury. Patients who reported suffering a previous injury were 2.21 (95% confidence interval=1.38, 3.53, p=0.001) times more likely to suffer a future LE MSK injury.

Conclusion: Ankle DF ROM asymmetry, SLAR asymmetry, SLHOP asymmetry, and iLESS performance are not related to LE MSK injury and therefore may not be helpful in identifying high school athletes at greatest risk of injury. Future research should evaluate the predictive power of other functional performance tests. Injury history was directly related to an increased likelihood of future injury, highlighting the need to obtain accurate injury history to identify individuals requiring further medical evaluation to mitigate time loss LE MSK injury risk.

INTRODUCTION

Although athletic participation comes with many benefits, it also comes with an inherent risk of lower extremity (LE) musculoskeletal (MSK) injury. In an attempt to reduce incidence of injuries, and their long term implications[143–152,164], methods for identifying individuals who are more likely to suffer injuries during sport participation have received increased attention. However, no gold standard for doing so has been established.[27–29,120] This gap in knowledge may result from a lack of understanding of factors that contribute to injury indirectly. Researchers often examine how individual factors contribute directly to injury and not how combinations of factors may alter risk. Modeling how factors jointly contribute to injury through a combination of direct and indirect effects may result in a more accurate understanding of LE MSK injury risk that may better inform prediction methods.

Potential predictors of injury risk that are often studied include functional performance asymmetries and drop landing mechanics.[13,17,22,26,103] Although direct relationships between functional performance asymmetry and LE MSK injury risk have been studied, findings are inconclusive.[13,17,22,56] Relationships between ankle dorsiflexion (DF) range of motion (ROM),[13] LE postural control,[17] and LE power generation/landing control[22] asymmetries have been evaluated but there is no strong evidence of their predictive value. Landing mechanics during a drop vertical jump task have also been studied extensively in both laboratory and clinical settings but have demonstrated conflicting results.[25–27,103,120] Identifying indirect effects of functional performance asymmetries, as well as drop landing mechanics, on injury may result in a more accurate understanding of LE MSK injury risk that may better inform injury prediction methods and contribute to the ultimate goal of injury prevention.

The purpose of this study was to identify direct and indirect effects of the following functional assessments on odds of LE MSK injury: 1) Ankle DF ROM asymmetry; 2) LE postural control asymmetry; 3) LE power generation/landing control asymmetry; 4) landing technique during a drop landing task. We hypothesized that increased asymmetries would be directly and indirectly related to an increased likelihood of LE MSK injury (Figure 3). We also hypothesized that poor landing technique would be directly related to an increased likelihood of LE MSK injury (Figure 3).

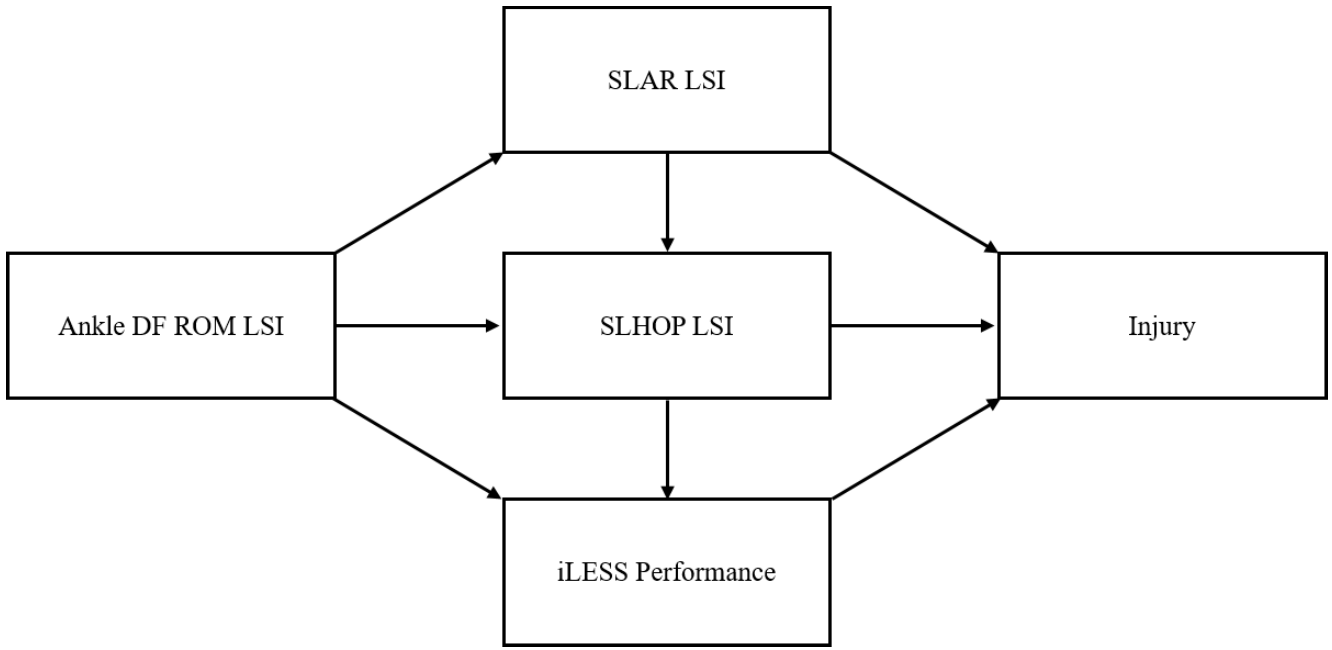


Figure 3. Hypothesized model in which functional performance influences lower extremity (LE) injury directly and indirectly. Ankle dorsiflexion (DF) range of motion (ROM) limb symmetry index (LSI) influences injury directly, as well as indirectly by influencing single leg anterior reach (SLAR) LSI, single leg hop for distance (SLHOP) LSI, and Impression Landing Error Scoring System (iLESS) performance. SLAR LSI influences injury directly, as well as indirectly by influencing SLHOP LSI and iLESS Performance. SLHOP LSI influences injury directly, as well as indirectly by influencing iLESS performance. iLESS performance influences injury directly.

METHODS

Subjects

This study consisted of high school athletes who were 13-19 years of age, members of a high school sponsored soccer or basketball team, and had been cleared by a medical professional to participate in athletics without restriction. Participants were eligible to participate multiple times if they played both sports or returned for testing in subsequent years. The study was approved by The Ohio State University institutional review board and participants provided informed consent or parental permission and informed assent prior to participation.

Data Collection

All testing was conducted prior to the start of each sport's competitive season during the 2013/2014 to 2015/2016 academic years as a part of the Functional Pre-Participation Physical Evaluation (FPPE) Project. Testing was performed in high school gymnasiums and athletic training facilities across the United States by certified athletic trainers (ATs). Prior to testing, ATs at each participating high school reviewed a standardized training manual developed by members of the FPPE research team. The manual included specifications for performing the tests as well as a standardized script to ensure participants received consistent instructions across all testing sites. After reviewing the manual, the ATs completed on site training conducted by a member of the FPPE team and passed a testing evaluation.

Demographics and Functional Performance Assessments

Prior to the functional assessment, each participant completed a questionnaire including age, sex, and sport. Participants reported any previous injuries using state mandated pre-participation physical evaluation (PPE) forms. Following the questionnaire, participants completed a functional performance assessment that evaluated Ankle DF ROM, LE postural control, and LE power generation/landing control asymmetries, as well as double leg landing mechanics.

Ankle DF ROM asymmetry was assessed using the weight bearing lunge test[165] (Figure 4). Each participant performed two trials per leg to obtain the farthest distance they were able to reach without lifting their heel off the ground. The score was recorded in centimeters as the furthest distance from the wall to the first toe of the stance leg.

Figure 4. Weight bearing ankle dorsiflexion (DF) range of motion (ROM) assessment.

Lower extremity postural control asymmetry was assessed with the single leg anterior reach (SLAR) test. The SLAR was conducted using only the anterior direction of the Y Balance Test (Functional Movement Systems, Danville, VA) and performed according to previously described protocols[166] (Figure 5). Participants performed a minimum of one practice trial on each leg followed by three testing trials per leg. Participants were instructed to alternate legs during testing trials. Reach distances for each limb were averaged and normalized to leg length (% LL). Leg length was measured from the anterior superior iliac spine to the medial malleolus.

Figure 5. Single leg anterior reach (SLAR).

Lower extremity power generation/landing control was assessed using the anterior, single leg hop for distance (SLHOP) test, which was performed according to previously described protocols[167,168] (Figure 6). Participants began in a single-leg stance, with the toes of the stance leg in line with the start of the tape measure. Participants then hopped forward as far as possible along the measurement line and landed on the same stance leg. Participants were required to maintain postural control upon landing for at least two seconds. Participants were asked to perform a minimum of one practice jump per leg to become familiar with the task, then three alternating maximum effort trials per leg. Jump distances were measured at the 1st toe to the nearest tenth centimeter. The average of the three trials was then normalized to limb length (% LL) and used for subsequent statistical analyses.

Figure 6. Anterior single leg hop for distance (SLHOP).

Double leg landing mechanics were assessed using the Impression Landing Error Scoring System (iLESS) (Figure 7). To complete a trial, the participant stood on top of a 30-cm tall box and leaned forward. Once they felt like they were about to fall, they brought both feet off the box at the same time, dropped downward, landed with both feet, and immediately performed a maximum effort vertical jump with both arms extended overhead. Each participant performed a minimum of one practice trial, followed by three drop landing trials. The iLESS had two possible scores, 0 or 1, based on the real-time clinician observation. A score of 0 meant a low risk/excellent movement pattern, while a score of 1 meant a high risk/poor movement pattern. Criteria used to evaluate movement patterns included knee valgus and knee flexion at initial contact, and knee valgus and knee flexion displacement from initial contact to maximum knee flexion. If the participant jumped off of the box, landed on one leg first, or did not perform a maximum effort vertical jump, the trial was discarded and repeated until three successful trials were completed.

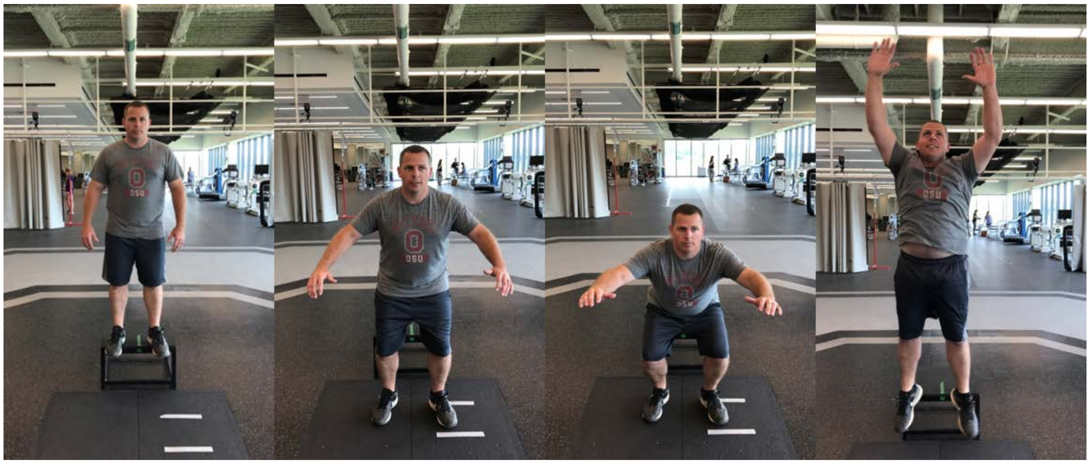


Figure 7. Impression Landing Error Scoring System (iLESS).

Injury Surveillance

Lower extremity MSK injury data were reported by ATs weekly using the national injury surveillance system High School Reporting Information Online (RIO™). In-depth explanations of this surveillance system have been described previously.[153] Detailed reports were provided for each injury and included information such as the body site (e.g. knee, hip), diagnosis (e.g. sprain, strain), time lost (e.g. < 1 week, 1-3 weeks), and the injury mechanism (e.g. contact with another person, non-contact). An injury was defined as an injurious event resulting from participation in an organized high school athletic practice or competition that required medical attention from an AT or a physician and restricted the athlete's participation in their sport for at least one day. Lower extremity MSK injuries included injuries to the foot/toe, ankle, lower leg, knee, thigh/upper leg, and hip.

Statistical Analysis

Ankle DF ROM, SLAR, and SLHOP limb symmetry indices (LSI) were calculated prior to statistical analyses. Ankle DF ROM, SLAR and SLHOP LSI were calculated as the ratio of the lower average distance to the higher average distance. The following is an example of a SLHOP LSI calculation:

$$\text{SLHOP LSI} = \frac{\text{lower average hop distance of the two limbs}}{\text{higher average hop distance of the two limbs}}$$

Athletes were also categorized as having either a good or poor iLESS performance based on the number of poor landings in their three trials. If any of their three attempts were categorized as a poor landing (i.e. given a score of 1), they were categorized as having a poor iLESS performance; they received score of 0 otherwise. A dichotomous injury history variable (i.e. scored "0" or "1") was also created for statistical analysis. Individuals were categorized as having a previous injury (i.e. score of "1") if they self-reported suffering any previous injury on their PPE form.

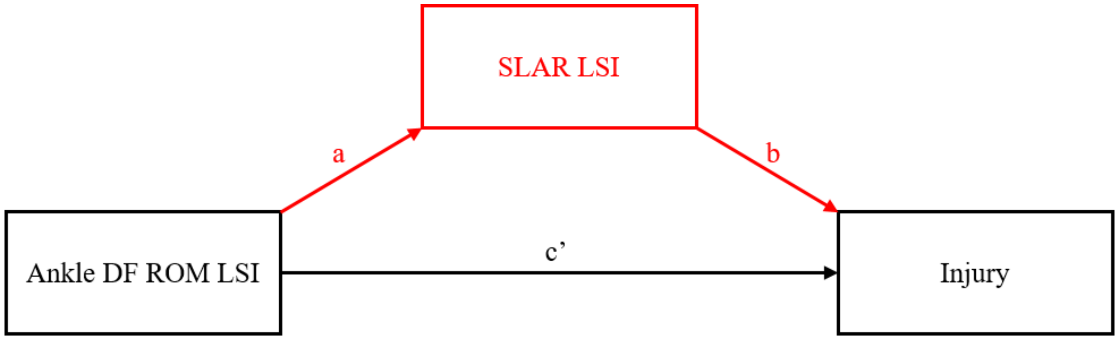
Descriptive statistics were calculated for each functional assessment by injury category. Statistical modeling was performed using a training and testing set. The training and testing consisted of approximately 70% (n = 2,534) and 30% (n = 1,025) of the data, respectively, and was split using stratified random sampling with strata of school, sport, and sex. Assessment of direct and indirect effects of functional assessments on LE MSK injury was performed in three steps:

Step 1: Establish Relationships between Functional Assessments

Relationships among ankle DF ROM, SLAR, and SLHOP asymmetries were assessed using three separate mixed effects linear regressions with random intercepts for school and athlete nested within school. Since iLESS performance was a dichotomous variable, relationships between this functional assessment and the other functional performance asymmetries were performed using three separate mixed effects logistic regressions with random intercepts for school and athlete nested within school. Each analysis was performed while controlling for effects of age, sex, and injury history.

Step 2: Perform Exploratory Analyses of Direct and Indirect Effects of Functional Assessments on Odds of LE MSK Injury

Exploratory analyses were performed on the training set consisting of approximately 70% of the sample data. Direct and indirect effects of functional assessments on odds of LE MSK injury were analyzed using a combination of mixed effects linear regression and mixed effects logistic regression with random intercepts for school and athlete nested within school. The analyzed effects were based on the relationships established in step 1; an example of an indirect effect is provided in Figure 8. Analyses were performed while controlling for effects of age, sex, and injury history. Statistical significance of indirect effects was assessed using 95% bootstrapped confidence intervals; an indirect effect was considered statistically significant if the 95% bootstrapped confidence interval didn't include 0.00.



Pathway	Equation
a	SLAR LSI = B_0 + B*Ankle DF ROM LSI + e
b	Injury = B_0 + B_1*Ankle DF ROM LSI + B_2*SLAR LSI + e
Indirect effect	B*B_2

Figure 8. Example of an indirect effect of ankle dorsiflexion (DF) range of motion (ROM) limb symmetry index (LSI) on injury through its effect on single leg anterior reach (SLAR) LSI. This example is illustrating that changes in ankle DF ROM LSI alter SLAR LSI (i.e. coefficient “B” from pathway “a”) which in turn influences the odds of injury (i.e. coefficient “B2” from pathway “b”). The indirect effect is the product of coefficients “B” and “B2.” Pathway “c’” denotes the direct effect of ankle DF ROM LSI on injury.

Step 3: Perform Confirmatory Analyses of Direct and Indirect Effects of Functional Assessments on Odds of LE MSK Injury

Direct and indirect effects identified as statistically significant in step 2 were validated using the testing set. Effects were analyzed using a combination of mixed effects linear regression and mixed effects logistic regression with random intercepts for school and athlete nested within school. Analyses were performed while controlling for effects of age, sex, and injury history. Statistical significance of indirect effects was assessed using 95% bootstrapped confidence intervals; an indirect effect was considered statistically significant if the 95% bootstrapped confidence interval didn't include 0.00.

All statistical analyses were performed with SAS version 9.4 (SAS Institute, Cary, NC). Statistical significance was determined *a priori* at $p \leq 0.05$. Assessing indirect effects of functional assessments on odds of LE MSK injury required the largest sample size to achieve sufficient power. A simulation study by Fritz et al. stated that 558 subjects would be needed to identify a small indirect effect using the percentile bootstrap method of significance testing at an alpha level of 0.05 and a desired power of 0.80.[169]

RESULTS

Since participants were eligible to participate multiple times, this study included 1,811 male cases from 1,384 individual males (age = 15.66±1.22 years, height = 1.77±0.09 m, weight = 68.97±13.15 kg) and 1,748 female cases from 1,261 individual females (age = 15.49±1.17 years, height = 1.65±0.07 m, weight = 60.54±10.12 kg). Descriptive statistics for injured and uninjured individuals are provided in Table 11.

Counts and proportions of injuries by body part and specific diagnosis are provided in tables 12 and 13. During the study 349 LE MSK injuries were reported. The ankle (n=132, 37.82%) and knee (n=80, 22.92%) were the two most commonly injured body parts for both sexes. The two most common injury diagnoses among boys' were ligament sprains (n=81, 46.55%) and muscle/tendon strains (n=17.24%). The two most common injury diagnoses among girls' were ligament sprains (n=79, 45.14%) and injuries classified as "other" (n=30, 17.14%). Muscle/tendon strains accounted for the third most injuries in girls' soccer and basketball (n=29, 16.57%).

Table 11. Demographics and functional assessments by injury status

	Injured	Uninjured
Ankle DF ROM LSI (%)[a]	87.50 (13.68)	87.90 (13.64)
SLAR LSI (%)[a]	95.61 (4.06)	95.70 (3.86)
SLHOP LSI (%)[a]	94.98 (5.38)	94.81 (4.72)
iLESS Performance[b]		
Poor	214 (61.32%)	2025 (63.58%)
Good	135 (38.68%)	1160 (36.42%)
Age (years)[a]	15.76 (1.23)	15.56 (1.19)
Height (m)[a]	1.72 (0.11)	1.71 (0.10)
Weight (kg)[a]	65.96 (12.71)	64.71 (12.47)
Sex[b]		
Male	174 (49.86%)	1635 (51.19%)
Female	175 (50.14%)	1559 (48.81%)
Sport[b]		
Soccer	150 (42.98%)	1565 (49.00%)
Basketball	199 (57.02%)	1629 (51.00%)
Injury History[b]		
No Previous Injury	224 (64.74%)	2526 (82.50%)
Previous Injury	122 (35.26%)	536 (17.50%)

Note: DF ROM = Dorsiflexion range of motion; iLESS = Impression Landing Error Scoring System; LSI = Limb symmetry index; SLAR = Single leg anterior reach; SLHOP = Single leg hop for distance

[a]Values are mean (standard deviation)

[b]Values are count (%)

Table 12. Counts and proportions of injuries by body part

	Males	Females	Total
Foot	11 (6.32)	16 (9.14)	27 (7.74)
Ankle	71 (40.80)	61 (34.86)	132 (37.82)
Lower leg	16 (9.20)	15 (8.57)	31 (8.88)
Knee	33 (18.97)	47 (26.86)	80 (22.92)
Thigh/upper leg	17 (9.77)	19 (10.86)	36 (10.32)
Hip	26 (14.94)	17 (9.71)	43 (12.32)
Total	174 (100.00)	175 (100.00)	349 (100.00)

Values are counts (%)

Table 13. Counts and proportions of injuries by specific diagnosis

	Males	Females	Total
Ligament sprain	81 (46.55)	79 (45.14)	160 (45.85)
Muscle/tendon strain	30 (17.24)	29 (16.57)	59 (16.91)
Fracture	9 (5.17)	9 (5.14)	18 (5.16)
Dislocation/subluxation	3 (1.72)	7 (4.00)	10 (2.87)
Contusion	24 (13.79)	21 (12.00)	45 (12.89)
Other	27 (15.52)	30 (17.14)	57 (16.33)
Total	174 (100.00)	175 (100.00)	349 (100.00)

Values are counts (%)

Relationships among Functional Assessments

Exploratory analyses of relationships among functional assessments using data from the training set (n = 2,534) are presented in Table 14. Single leg anterior reach LSI was significantly related to SLHOP LSI independent of age, sex, sport, and injury history (B = 0.17, 95%CI = 0.13, 0.22, $p < 0.001$). No other relationships were statistically significant. As a result, an indirect effect of SLAR LSI on injury through SLHOP LSI was assessed using the training set.

Table 14. Exploratory analysis of relationships among functional assessments

Predictor	Outcome	Coefficient	95%CI		SE	p-value	Odds Ratio	Odds Ratio 95%CI	
Ankle DF LSI	SLAR LSI	0.003	-0.01	0.01	0.01	0.62	-	-	-
Ankle DF LSI	SLHOP LSI	0.005	-0.01	0.02	0.01	0.48	-	-	-
Ankle DF LSI	iLESS Performance	0.35[a]	-0.34[a]	1.05[a]	0.35	0.32	1.42	0.71	2.84
SLAR LSI	SLHOP LSI	0.17	0.13	0.22	0.02	< 0.001[b]	-	-	-
SLAR LSI	iLESS Performance	1.08[a]	-1.36[a]	3.52[a]	1.24	0.38	2.94	0.26	33.71
SLHOP LSI	iLESS Performance	-1.25[a]	-3.33[a]	0.83[a]	1.06	0.24	0.29	0.04	2.30

Note: CI = Confidence interval; DF ROM = Dorsiflexion range of motion; iLESS = Impression Landing Error Scoring System; LSI = Limb symmetry index; SE = Standard error; SLAR = Single leg anterior reach; SLHOP = Single leg hop for distance; Relationships are assessed while controlling for age, sex, sport, and injury history

[a]Values are in log odds

[b]Statistically significant at $p \leq 0.05$

Exploratory Analyses of Direct and Indirect Effects

Functional performance assessments were not directly related to injury independent of age, sex, sport, and injury history. Age (odds ratio [OR] = 1.17, 95%CI = 1.04, 1.32, $p = 0.01$) and injury history (OR = 2.38, 95%CI = 1.73, 3.28, $p < 0.001$) were significantly related to odds of LE MSK injury independent of sex, sport, and all four functional assessments (Table 15). The indirect effect of SLAR LSI on injury was insignificant (OR = 0.90, 95%CI = 0.58, 1.49) (Figure 9). As a result, confirmatory analyses of the relationships between age or injury history and LE MSK injury were performed using the testing set.

Table 15. Exploratory analysis of direct effects of demographics and functional assessments on injury

Predictor	Outcome	Coefficient[e]	95%CI		SE	p-value	Odds Ratio	Odds Ratio 95%CI	
SLAR LSI	Injury	-1.72	-5.36	1.92	1.85	0.35	0.18	0.005	6.84
SLHOP LSI	Injury	-0.66	-3.68	2.36	1.54	0.67	0.52	0.03	10.58
iLESS Performance[a]	Injury	-0.09	-0.40	0.22	0.16	0.56	0.91	0.67	1.24
Ankle DF ROM LSI	Injury	-0.61	-1.57	0.35	0.49	0.21	0.54	0.21	1.41
Age	Injury	0.16	0.04	0.28	0.06	0.01[f]	1.17	1.04	1.32
Sex[b]	Injury	0.14	-0.16	0.44	0.15	0.36	1.15	0.85	1.55
Injury History[c]	Injury	0.87	0.55	1.19	0.16	< 0.001[f]	2.38	1.73	3.28
Sport[d]	Injury	0.07	-0.23	0.36	0.15	0.67	1.07	0.79	1.44

Note: CI = Confidence interval; DF ROM = Dorsiflexion range of motion; iLESS = Impression Landing Error Scoring System; LSI = Limb symmetry index; SE = Standard error; SLAR = Single leg anterior reach; SLHOP = Single leg hop for distance

[a]iLESS good performance is reference group

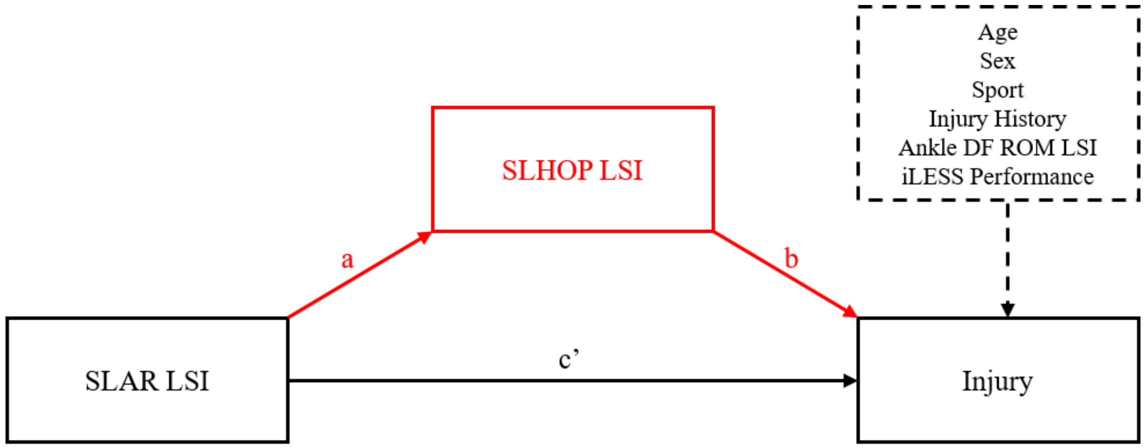
[b]Males are reference group

[c]No previous injury is reference group

[d]Soccer is reference group

[e]Values are in log odds

[f]Statistically significant at $p \leq 0.05$



Pathway	Coefficient	95%CI	p-value
a	0.17	0.12, 0.22	< 0.001
b	-0.66	-3.68, 2.36	0.67
Indirect effect	-0.11	-0.54, 0.40	-
c’	-1.72	-5.36, 1.92	0.35

Figure 9. Results from mediation analyses. All analyses were performed controlling for age, sex, sport, injury history, ankle dorsiflexion (DF) range of motion (ROM) limb symmetry index (LSI), and Impression Landing Error Scoring System (iLESS) performance. Coefficient and 95% confidence interval (95%CI) for pathway “a” is the effect of single leg anterior reach (SLAR) LSI on single leg hop for distance (SLHOP) LSI in original LSI units. Coefficients and 95%CI for pathways “b” and “c’” are in log odds and are the effects of SLHOP LSI and SLAR LSI on injury, respectively. Indirect effect of SLAR LSI on injury is the product of the coefficients from pathways “a” and “b”. Coefficient and 95%CI for the indirect effect are in log odds. 95%CI for the indirect effect is a percentile bootstrapped CI. Coefficient with a p-value ≤ 0.05 or 95%CI that doesn’t include “0.00” is considered statistically significant. No p-value for the indirect effect was calculated since statistical significance was determined by the 95% bootstrapped confidence interval.

Confirmatory Analyses of Direct and Indirect Effects

Confirmatory analyses of relationships between age, or injury history, and odds of LE MSK injury using data from the testing set (n = 1,025) are presented in Table 16. Injury history was significantly related to odds of LE MSK injury (OR = 2.21, 95%CI = 1.38, 3.53, p = 0.001). Age was not significantly related to LE MSK injury.

Table 16. Confirmatory analysis of direct effects of age and injury history on injury

Predictor	Outcome	Coefficient[b]	95%CI		SE	p-value	Odds Ratio	Odds Ratio 95%CI	
Age	Injury	0.18	-0.001	0.36	0.09	0.051	1.19	0.99	1.43
Injury History[a]	Injury	0.79	0.32	1.26	0.24	0.001[c]	2.21	1.38	3.53

Note: CI = Confidence interval; SE = Standard error
[a]No previous injury is reference group
[b]Values are in log odds
[c]Statistically significant at $p \leq 0.05$

DISCUSSION

This study aimed to identify direct and indirect effects of functional assessments on odds of LE MSK injury in in boys' and girls' high school soccer and basketball athletes. Contrary to our hypotheses, functional assessments were not related, directly or indirectly, to injury independent of age, sex, sport, and injury history. Previous injury was a significant predictor of subsequent LE MSK injury in boys' and girls' high school soccer and basketball athletes. Specifically, odds of injury were greater among individuals with a history of injury while controlling for other variables of interest. These findings indicate the need to accurately assess injury history during the PPE process.

Functional Performance

Ankle DF ROM LSI

Functional performance asymmetries, as well as drop landing performance, were not directly related to LE MSK injury odds after controlling for age, sex, sport, and injury history. The lack of association between ankle DF ROM LSI and LE MSK injury is contradictory to previous research by Soderman et al.[13] Soderman et al. identified that increased ankle DF ROM asymmetry was related to overuse leg injury.[13] This difference may be attributed to our inclusion of time loss injuries only which likely excluded some overuse injuries.

SLAR LSI

The lack of a direct association between SLAR LSI and injury was also contradictory to previous research performed on high school and college athletes.[17,170] The differing results may have resulted from testing protocol variations. Studies suggesting SLAR asymmetry is indicative of increased injury risk were performed as a part of the SEBT,[17,170] which does not require the Y-Balance test kit that was used in our study. Researchers have demonstrated that anterior reach performance may differ between the SEBT and Y-Balance test and therefore our findings may be a result of different test demands.[171,172] SLAR LSI was not indirectly associated with injury, despite the direct relationship between SLAR LSI and SLHOP LSI. Although increases in SLAR LSI were associated with increases in SLHOP LSI, they did not result in subsequent increases in odds of injury. The insignificant indirect effect was likely due to the lack of a direct relationship between SLHOP LSI and injury.

SLHOP LSI

Similar to ankle DF ROM LSI and SLAR LSI, SLHOP LSI was not significantly related to LE MSK injury. Our findings differ from those of Brumitt et al. who identified that the odds of injury was greater among females with SLHOP asymmetries greater than 10%. This study was performed in division III collegiate athletes however, potentially explaining the outcome differences.

iLESS Performance

The relationship between iLESS performance and injury was not statistically significant. This finding is similar to those of Smith et al. who did not identify adequate predictive validity of the Landing Error Scoring System (LESS) in high school and college athletes.[27]This finding is contradictory to research by Padua et al. on the LESS as a predictor of ACL injury.[24,27] Padua et al. identified an increased risk of ACL injury in elite youth soccer players with poor jump landing techniques.[24] The difference in our findings and those of Padua et al. may be explained by our intent to identify risk of any time-loss LE MSK injury. We did not analyze ACL injury individually due to the limited number of ACL injuries (< 15) in our sample so the ability for the iLESS to identify that particular injury is unclear. The limited ability of the iLESS to identify likelihood of injury may also be due to its scoring structure. Small deficits may not be captured by the dichotomous scoring scheme, likely limiting the sensitivity of the assessment.

Injury History

Injury history was associated with LE MSK injury following confirmatory data analysis. Odds of sustaining a LE MSK injury were twice as likely among patients who reported sustaining a previous injury were. This finding is consistent with research across a variety of study populations.[8,9,67,173] Individuals with a history of ankle sprains may be 5 times more likely to sustain a future ankle sprain than individuals with no prior ankle sprains.[67] Similarly, individuals with a previous ACL injury may be 3 times more likely to suffer a future ACL injury than individuals with no prior ACL injury.[173] The association between previous and future injury may be due to residual mobility, postural control, or strength impairments following initial injury. Schmitt et al. demonstrated that quadriceps strength deficits following ACL reconstruction negatively influence function and hop test performance.[174] These impairments, if not properly rehabilitated, may persist, increasing future injury risk. These findings highlight the need for accurate injury history reporting during PPEs in order to identify individuals who need further medical evaluation to mitigate future injury risk.

Limitations

Results from this study are based on soccer and basketball athletes, and therefore cannot be generalized to other high school sport. Since we only included high school athletes we cannot generalize our results to soccer and basketball athletes of other competition levels (e.g. youth, college). Also, by including time loss injuries only our results don't reflect direct and indirect effects of functional performance assessments on risk of non-time loss LE MSK injuries. It is important to note that we did not record athlete-exposures, such as numbers of games and practices participated in, due to our concern with our ability to accurately capture exposure data. Thus, the outcome variable is not injury rate. Lastly, injury history was self-reported and thus possibly underreported.

CONCLUSION

Identifying direct and indirect effects of functional performance asymmetries, as well as drop landing mechanics, on injury may result in a more accurate understanding of LE MSK injury risk that may better inform injury prediction methods and contribute to the ultimate goal of injury prevention. This study indicates that ankle DF ROM LSI, SLAR LSI, SLHOP LSI, and iLESS performance are neither directly nor indirectly related to odds of LE MSK injury in high school soccer and basketball players. Additional functional performance tests, as well as more sensitive measures of functional performance, should be evaluated in an attempt to better identify individuals at increased risk of injury. Injury history was directly related to an increased likelihood of future injury. This finding highlights the need to obtain accurate injury history to identify individuals requiring further medical evaluation to mitigate time loss LE MSK injury risk.

Chapter 5: Functional Asymmetries, Functional Performances, and Lower Extremity Injury: A Moderation Analysis

ABSTRACT

Background: Athletic participation provides many physical, emotional, and social benefits but it also comes with an inherent risk of lower extremity (LE) musculoskeletal (MSK) injury. Methods for identifying individuals most likely to suffer injuries during sport participation have been studied in an attempt to intervene and reduce injury incidence but no gold standard has been established for doing so. This gap in knowledge may result from a lack of research into moderators of injury risk.

Purpose: Determine if relationships between functional asymmetries and LE MSK injury risk are moderated by functional performances in boys' and girls' high school soccer and basketball athletes.

Methods: Data for this study were prospectively collected among male and female athletes ages 13-19 on a high school sponsored soccer or basketball team. Prior to the start of their competitive sport season participants performed three tests to assess functional performance and asymmetry. These tests consisted of ankle dorsiflexion (DF) range of motion, single leg anterior reach (SLAR), and anterior single leg hop for distance (SLHOP) tests. Participant questionnaires also captured age, sex, sport, and injury history. LE MSK injury data were reported throughout each sport season by certified athletic trainers using the injury surveillance system High School Reporting Information Online. Mixed effects logistic regressions were used to determine if effects of ankle DF ROM limb symmetry index (LSI), SLAR LSI, and SLHOP LSI on injury were moderated by ankle DF ROM performance, SLAR performance, and SLHOP performance, respectively.

Results: 1,384 males (age=15.66±1.22 years, height=1.77±0.09 m, weight=68.97±13.15 kg) and 1,261 females (age=15.49±1.17 years, height=1.65±0.07 m, weight=60.54±10.12 kg) participated in this prospective study. Age (OR = 1.20, 95%CI = 1.001, 1.44, p = 0.05) and injury history (OR = 2.19, 95%CI = 1.35, 3.54, p=0.002) were significantly related to LE MSK injury, although the effect of age was small. The odds of injury were 2 times greater among individuals who suffered a previous injury.

Conclusion: Effects of ankle DF ROM LSI, SLAR LSI, and SLHOP LSI on injury may not be moderated by ankle DF ROM performance, SLAR performance, and SLHOP performance, respectively. Additional functional performance tests should be evaluated in an attempt to better identify individuals at increased risk of injury. Injury history was directly related to an increased likelihood of future injury, highlighting the need to obtain accurate injury history to identify individuals requiring further medical evaluation to mitigate time loss LE MSK injury risk.

INTRODUCTION

Over 7.8 million high school students participate in athletics annually, placing a large proportion of adolescents at inherent risk of lower extremity (LE) musculoskeletal (MSK) injury.[2,140] In an attempt to reduce incidence of injuries, and their long term implications[143–152,164], methods for identifying individuals more likely to suffer injuries during sport participation have been studied. Despite previous efforts to identify individuals who are at greater risk of injury, no gold standard for doing so has been established.[27–29,120] This gap in knowledge may result from a lack of understanding of moderators of injury risk. Moderators alter the strength of association between a potential risk factor and LE MSK injury (Figure 10).[175,176] Current risk assessment models do not accurately evaluate moderators of injury which may contribute to the lack of a gold standard.

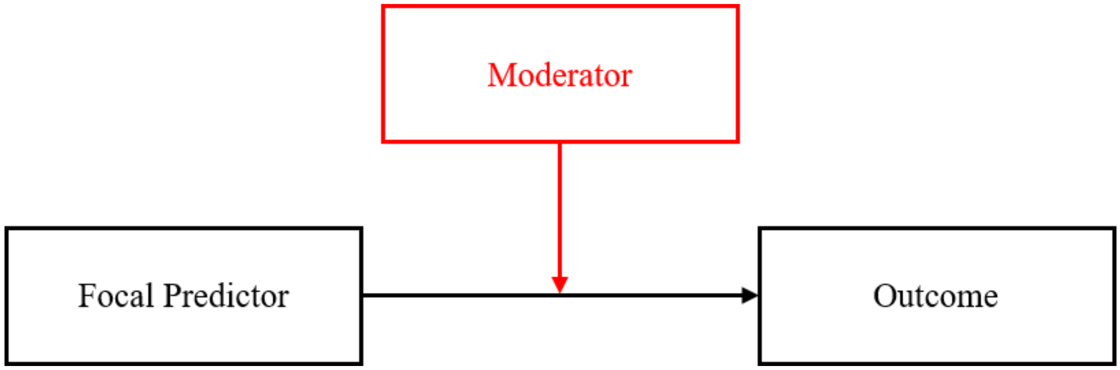


Figure 10. Graphical depiction of a moderated relationship. The effect of the focal predictor on the outcome varies as a function of (i.e. is moderated by) a third variable.

The need for identifying moderators of injury is particularly important for research on functional performance asymmetry and injury risk. Researchers often evaluate the influence of asymmetry on LE MSK injury independent of functional performance. As a result, the extent to which relationships between asymmetries and injury depend on functional performance is unclear. Potential predictors of injury risk that are often studied and for which understanding moderating effects would be beneficial are LE range of motion (ROM), postural control, and power generation/landing control asymmetries.[13,17,22] Although direct relationships between these asymmetries and LE MSK injury risk have been studied, findings are inconclusive.[13,17,22,56] Identifying moderators of LE MSK injury in adolescent athletes may help clinicians better identify individuals at an increased risk of injury who would benefit the most from injury prevention interventions.

The purpose of this study was to identify if effects of LE ROM asymmetry, LE postural control asymmetry, and LE power generation/landing control asymmetry on odds of LE MSK injury were moderated by LE ROM performance, LE postural control performance, and LE power generation/landing control performance, respectively. We hypothesized that increases in asymmetry on a specific assessment would alter the likelihood of injury to a greater extent among individuals who performed poorly on the same assessment compared to individuals with average or above average performances.

METHODS

Subjects

This study consisted of high school athletes who were 13-19 years of age, members of a high school sponsored soccer or basketball team, and had been cleared by a medical professional to participate in athletics without restriction. Participants were eligible to participate multiple times if they played both sports or returned for testing in subsequent years. The study was approved by The Ohio State University institutional review board and participants provided informed consent or parental permission and informed assent prior to participation.

Data Collection

All testing was conducted prior to the start of each sport's competitive season during the 2013/2014 to 2015/2016 academic years as a part of the Functional Pre-Participation Physical Evaluation (FPPE) Project. Testing was performed in high school gymnasiums and athletic training facilities across the United States by certified athletic trainers (ATs). Prior to testing, ATs at each participating high school reviewed a standardized training manual developed by members of the FPPE research team. The manual included specifications for performing the tests as well as a standardized script to ensure participants received consistent instructions across all testing sites. After reviewing the manual, the ATs completed on site training conducted by a member of the FPPE team and passed a testing evaluation.

Demographics and Functional Performance Assessments

Prior to the functional assessment, each participant completed a questionnaire including age, sex, and sport. Participants reported any previous injuries using state mandated pre-participation physical evaluation (PPE) forms. Following the questionnaire, participants completed a functional performance assessment that evaluated ankle dorsiflexion (DF) ROM, LE postural control, and LE power generation/landing control.

Ankle DF ROM was assessed using the weight bearing lunge test[165] (Figure 4). Each participant performed two trials per leg to obtain the farthest distance they were able to reach without lifting their heel off the ground. The score was recorded in centimeters as the furthest distance from the wall to the first toe of the stance leg.

Lower extremity postural control was assessed with the single leg anterior reach (SLAR) test. The SLAR was conducted using only the anterior direction of the Lower Quarter Y Balance Test (Functional Movement Systems, Danville, VA) and performed according to previously described protocols[166] (Figure 5). Participants performed a minimum of one practice trial on each leg followed by three testing trials per leg. Participants were instructed to alternate legs during testing trials. Reach distances for each limb were averaged and normalized to leg length (% LL). Leg length was measured from the anterior superior iliac spine to the medial malleolus.

Lower extremity power generation/landing control was assessed using the anterior, single leg hop for distance (SLHOP) test, which was performed according to previously described protocols[167,168] (Figure 6). Participants began in a single-leg stance, with the toes of the stance leg in line with the start of the tape measure. Participants then hopped forward as far as possible along the measurement line and landed on the same stance leg. Participants were required to maintain postural control upon landing for at least two seconds. Participants were asked to perform a minimum of one practice jump per leg to become familiar with the task, then three alternating maximum effort trials per leg. Jump distances were measured at the 1st toe to the nearest tenth centimeter. The average of the three trials was then normalized to limb length (% LL) and used for subsequent statistical analyses.

Injury Surveillance

Lower extremity MSK injury data were reported by ATs weekly using the national injury surveillance system High School Reporting Information Online (RIO™). In-depth explanations of this surveillance system have been described previously.[153] Detailed reports were provided for each injury and included information such as the body site (e.g. knee, hip), diagnosis (e.g. sprain, strain), time lost (e.g. < 1 week, 1-3 weeks), and the injury mechanism (e.g. contact with another person, non-contact). An injury was defined as an injurious event resulting from participation in an organized high school athletic practice or competition that required medical attention from an AT or a physician and restricted the athlete's participation in their sport for at least one day. Lower extremity MSK injuries included injuries to the foot/toe, ankle, lower leg, knee, thigh/upper leg, and hip.

Statistical Analysis

A dichotomous injury history variable (i.e. scored "0" or "1") was also created for statistical analysis. Individuals were categorized as having a previous injury (i.e. score of "1") if they self-reported suffering any previous injury on their PPE form. Average ankle DF ROM, SLAR, and SLHOP performances, as well as limb symmetry indices (LSI), were calculated prior to statistical analyses. Performances were calculated as the average distance across limbs. Limb symmetry indices were calculated as the ratio of the lower average distance of the two limbs to the higher average distance of the two limbs. The following is an example of a SLAR LSI calculation:

$$\text{SLAR LSI} = \frac{\text{lower average reach distance of the two limbs}}{\text{higher average reach distance of the two limbs}}$$

Descriptive statistics were calculated for each functional assessment by injury category. Statistical modeling was performed using a training and testing set. The training and testing consisted of approximately 70% (n = 2,534) and 30% (n = 1,025) of the data, respectively, and was split using stratified random sampling with strata of school, sport, and sex. A two-step process was used to determine if effects of functional assessment asymmetries on LE MSK injury varied based on functional assessment performances.

Step 1: Perform Exploratory Analyses of Moderated Effects

Exploratory analyses were performed on the training set consisting of approximately 70% of the sample data. Three separate mixed effects logistic regression models with random intercepts for school and athlete nested within school were used to determine if effects of ankle DF ROM LSI, SLAR LSI, and SLHOP LSI on LE MSK injury were moderated by ankle DF ROM performance, SLAR performance, and SLHOP performance, respectively (Figure 11). Analyses were performed while controlling for age, sex, sport, and injury history. Moderation was assessed using an interaction term between corresponding LSI and performance variables with statistically significant interactions indicating moderated effects. If a moderated effect was statistically significant the pick-a-point approach[175,177] was used to identify the values of the moderator (i.e. the corresponding performance variable) at which the effect of LSI on injury was statistically significant. Specifically, the effect of LSI on injury was evaluated when the moderator was equal to its average, one standard deviation (SD) below average, and one SD above average. These points were chosen as measures of average, relatively low, and relatively high performances, respectively.

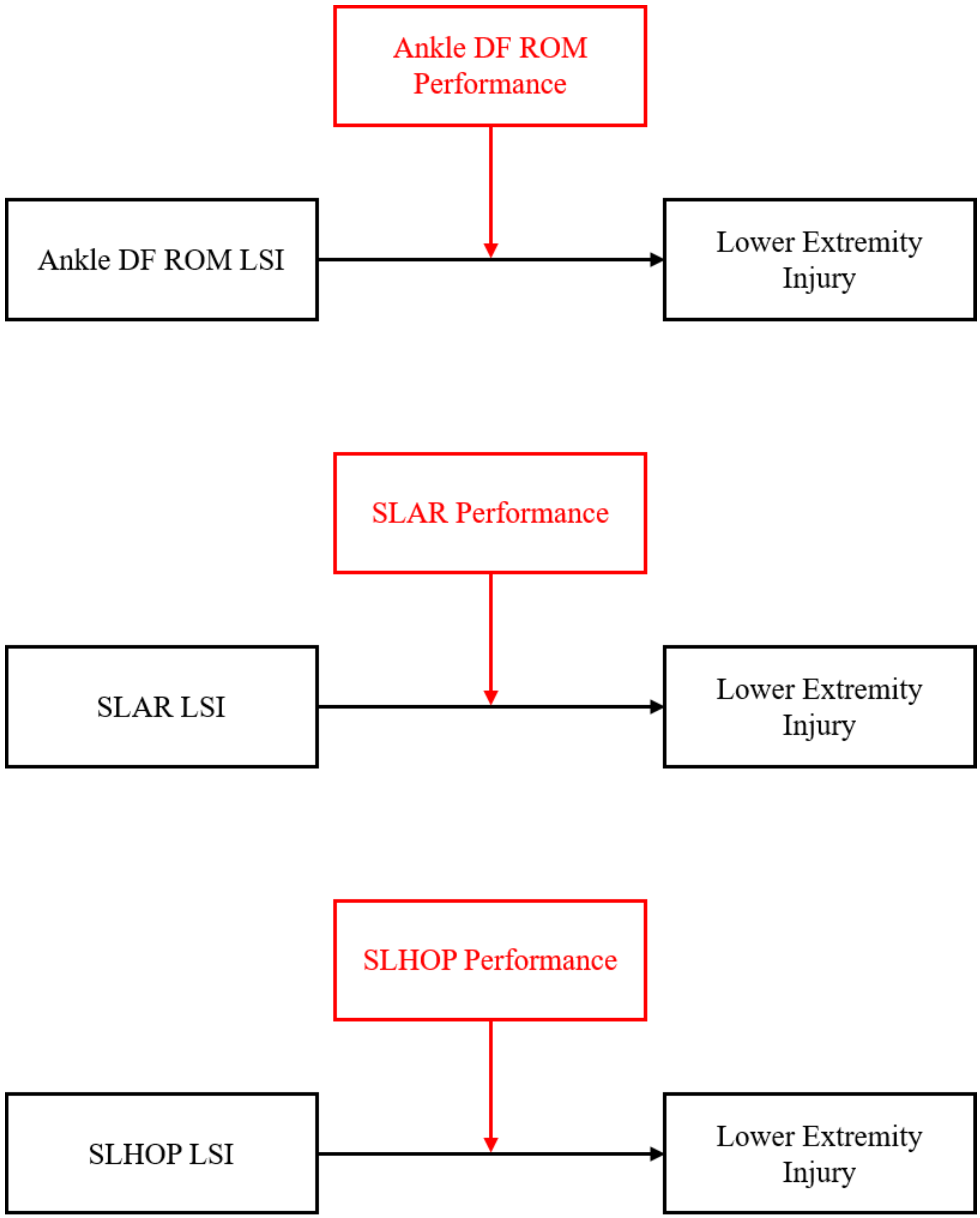


Figure 11. Three separate models of functional performance as a proposed moderator of the relationship between functional asymmetry and lower extremity injury. DF ROM = dorsiflexion range of motion, LSI = limb symmetry index, SLAR = single leg anterior reach, SLHOP = single leg hop for distance.

Step 2: Perform Confirmatory Analyses

Significant relationships identified in step 1 were validated using the testing set which comprised approximately 30% of the sample data. As was performed in step 1, mixed effects logistic regression models with random intercepts for school and athlete nested within school were used for validation analyses. Analyses were performed while controlling for age, sex, sport, and injury history. If moderation was deemed significant in step 1 and confirmed in step 2, the relationship was examined further using the pick-a-point approach.

All statistical analyses were performed with SAS version 9.4 (SAS Institute, Cary, NC). Statistical significance was determined *a priori* at $p \leq 0.05$. Power analyses identified that 522 participants were needed to identify an odds ratio of 1.5 at an alpha level of 0.05 and 80% power assuming a probability of injury of 0.10.

RESULTS

Since participants were eligible to participate multiple times this study included 1,811 male cases from 1,384 individual males (age = 15.66±1.22 years, height = 1.77±0.09 m, weight = 68.97±13.15 kg) and 1,748 female cases from 1,261 individual females (age = 15.49±1.17 years, height = 1.65±0.07 m, weight = 60.54±10.12 kg). Descriptive statistics for injured and uninjured individuals are provided in Table 11. Counts and proportions of injuries by body part and specific diagnosis are provided in tables 12 and 13. During the study 349 LE MSK injuries were reported. The ankle (n=132, 37.82%) and knee (n=80, 22.92%) were the two most commonly injured body parts for both sexes. The two most common injury diagnoses among boys' were ligament sprains (n=81, 46.55%) and muscle/tendon strains (n=17.24%). The two most common injury diagnoses among girls' were ligament sprains (n=79, 45.14%) and injuries classified as "other" (n=30, 17.14%). Muscle/tendon strains accounted for the third most injuries in girls' soccer and basketball (n=29, 16.57%).

Exploratory Analyses of Moderated Effects

Ankle Dorsiflexion Range of Motion

Ankle DF ROM performance did not show a moderation effect on the relationship between ankle DF ROM LSI and LE injury independent of age, sex, sport, and injury history (Table 17). Neither ankle DF ROM LSI (odds ratio [OR] = 0.52, 95%CI = 0.19, 1.45, $p = 0.21$) nor ankle DF ROM performance (OR = 1.00, 95%CI = 0.96, 1.05, $p = 1.00$) were related to injury in a secondary analysis when the interaction term was not included. Age (OR = 1.18, 95%CI = 1.05, 1.33, $p = 0.01$) and injury history (OR = 2.31, 95%CI = 1.67, 3.17, $p < 0.001$) were associated with LE MSK injury in this secondary analysis.

Table 17. Ankle dorsiflexion range of motion exploratory analysis

Predictor	Coefficient[e]	95%CI[e]		SE	p-value	Odds Ratio	Odds Ratio 95%CI	
Ankle DF ROM LSI	-0.66	-2.61	1.28	0.99	0.50	0.52	0.07	3.61
Ankle DF ROM Performance	0.00	-0.22	0.22	0.11	0.99	1.00	0.80	1.25
Interaction[a]	0.00	-0.25	0.25	0.13	0.99	1.00	0.78	1.29
Age	0.16	0.04	0.28	0.06	0.01[f]	1.18	1.05	1.33
Sex[b]	0.14	-0.16	0.44	0.15	0.35	1.15	0.86	1.55
Sport[c]	0.06	-0.24	0.37	0.15	0.68	1.07	0.79	1.44
Injury History[d]	0.84	0.52	1.16	0.16	<0.001[f]	2.31	1.67	3.18

Note: CI = Confidence interval; DF ROM = Dorsiflexion range of motion; LSI = Limb symmetry index; SE = Standard error

[a]Interaction is Ankle DF ROM LSI*Ankle DF ROM performance

[b]Males are reference group

[c]Soccer is reference group

[d]No previous injury is reference group

[e]Values are in log odds

[f]Statistically significant at $p \leq 0.05$

Single Leg Anterior Reach

Single leg anterior reach performance did not show a moderation effect on the relationship between SLAR LSI and LE injury independent of age, sex, sport, and injury history (Table 18). Neither SLAR LSI (OR = 0.15, 95%CI = 0.004, 5.60, p = 0.30) nor SLAR performance (OR = 1.01, 95%CI = 0.99, 1.02, p = 0.50) were related to injury in a secondary analysis even when the interaction term was not included. Age (OR = 1.18, 95%CI = 1.05, 1.33, p = 0.01) and injury history (OR = 2.36, 95%CI = 1.72, 3.25, p < 0.001) were associated with LE MSK injury in this secondary analysis.

Table 18. Single leg anterior reach exploratory analysis

Predictor	Coefficient[e]	95%CI[e]		SE	p-value	Odds Ratio	Odds Ratio 95%CI	
SLAR LSI	-22.10	-48.39	4.19	13.37	0.10	<0.0001	<0.0001	65.70
SLAR Performance	-0.27	-0.63	0.09	0.18	0.14	0.76	0.53	1.09
Interaction[a]	0.29	-0.09	0.67	0.19	0.13	1.34	0.92	1.95
Age	0.17	0.05	0.29	0.06	0.01[f]	1.18	1.05	1.33
Sex[b]	0.14	-0.15	0.44	0.15	0.34	1.16	0.86	1.56
Sport[c]	0.08	-0.23	0.38	0.15	0.62	1.08	0.80	1.46
Injury History[d]	0.87	0.55	1.19	0.16	<0.001[f]	2.39	1.74	3.30

Note: CI = Confidence interval; LSI = Limb symmetry index; SE = Standard error; SLAR = Single leg anterior reach

[a]Interaction is SLAR LSI*SLAR performance

[b]Males are reference group

[c]Soccer is reference group

[d]No previous injury is reference group

[e]Values are in log odds

[f]Statistically significant at $p \leq 0.05$

Single Leg Hop for Distance

Anterior single leg hop for distance performance did not show a moderation effect on the relationship between SLHOP LSI and LE injury independent of age, sex, sport, and injury history (Table 19). Anterior single leg hop for distance LSI (OR = 0.22, 95%CI = 0.01, 4.53, $p = 0.33$) was not related to injury in a secondary analysis that didn't include an interaction term for moderation. However, SLHOP performance (OR = 1.006, 95%CI = 1.001, 1.01, $p = 0.02$) was related to injury in the secondary analysis when the interaction term was not included. Age (OR = 1.15, 95%CI = 1.02, 1.30, $p = 0.02$) and injury history (OR = 2.26, 95%CI = 1.64, 3.12, $p < 0.001$) were also associated with LE MSK injury in this secondary analysis.

Table 19. Anterior single leg hop for distance exploratory analysis

Predictor	Coefficient[e]	95%CI[e]		SE	p-value	Odds Ratio	Odds Ratio 95%CI	
SLHOP LSI	-8.10	-22.85	6.64	7.50	0.28	<0.0001	<0.0001	766.93
SLHOP Performance	-0.03	-0.12	0.05	0.04	0.45	0.97	0.89	1.05
Interaction[a]	0.04	-0.05	0.13	0.04	0.37	1.04	0.95	1.13
Age	0.14	0.02	0.27	0.06	0.02[f]	1.16	1.02	1.30
Sex[b]	0.30	-0.04	0.64	0.17	0.09	1.35	0.96	1.89
Sport[c]	0.06	-0.24	0.37	0.16	0.68	1.07	0.79	1.45
Injury History[d]	0.82	0.49	1.14	0.16	<0.001[f]	2.26	1.64	3.12

Note: CI = Confidence interval; LSI = Limb symmetry index; SE = Standard error; SLHOP = Single leg hop for distance

[a]Interaction is SLHOP LSI*SLHOP performance

[b]Males are reference group

[c]Soccer is reference group

[d]No previous injury is reference group

[e]Values are in log odds

[f]Statistically significant at $p \leq 0.05$

Confirmatory Analyses of SLHOP Performance, Age, and Injury History

Confirmatory analyses of the effects of SLHOP performance, age, and injury history on LE injury using data from the testing set are presented in Table 20. Age (OR = 1.20, 95%CI = 1.001, 1.44, $p = 0.05$) and injury history (OR = 2.19, 95%CI = 1.35, 3.54, $p=0.002$) were significantly related to LE MSK injury. SLHOP performance was not significantly related to injury.

Table 20. Confirmatory analysis of effects of SLHOP performance, age, and injury history on injury

Predictor	Coefficient[b]	95%CI[b]		SE	p-value	Odds Ratio	Odds Ratio 95%CI	
SLHOP Performance	0.0004	-0.003	0.004	0.002	0.82	1.00	0.99	1.004
Age	0.18	0.001	0.37	0.09	0.05[c]	1.20	1.001	1.44
Injury History[a]	0.78	0.30	1.26	0.24	0.002[c]	2.19	1.35	3.54

Note: CI = Confidence interval; SE = Standard error; SLHOP = Single leg hop for distance

[a]No previous injury is reference group

[b]Values are in log odds

[c]Statistically significant at $p \leq 0.05$

DISCUSSION

This study aimed to identify if effects of ankle DF ROM LSI, SLAR LSI, and SLHOP LSI on LE injury were moderated by DF ROM performance, SLAR performance, and SLHOP performance, respectively. Contrary to our hypotheses, functional performance did not moderate relationships between asymmetry and injury independent of age, sex, sport, and injury history. Age and injury history were significantly related to future LE injury in boys' and girls' high school soccer and basketball. Specifically, the odds of injury were greater among older individuals. The odds of injury were also greater among individuals who self-reported suffering a previous injury. These findings indicate the need for recording accurate injury history during the PPE process to mitigate risk of injury during sport participation.

Functional Performance and Asymmetry

Ankle Dorsiflexion Range of Motion

Ankle DF ROM performance did not significantly moderate the relationship between ankle DF ROM LSI and injury, indicating that any potential relationship between LSI and injury did not vary as a function of performance. Additionally, secondary analyses indicated that neither DF ROM LSI nor DF ROM performance were related to LE injury independent of age, sex, sport, and injury history. The lack of association between ankle DF ROM LSI and LE MSK injury is contradictory to previous research by Soderman et al.[13] Soderman et al. identified that increased ankle DF ROM asymmetry was related to overuse leg injury.[13] This difference may be attributed to our inclusion of time loss injuries only which likely excluded some overuse injuries.

The lack of association between ankle DF ROM performance and injury was consistent with previous research.[12,46,99] Wang et al. did not find an association between ankle DF ROM and ankle injuries in high school basketball players.[99] Kaufman et al. did not find an association between reduced ankle DF ROM with the knee flexed and overuse injuries in the military.[12] Our finding is contradictory to a research study by Pope et al. which identified that the risk of an ankle sprain was greater among individuals with inflexible ankles when compared to individuals with average flexibility.[178] The contradictory findings may be due to differences in study methodologies. Pope et al.[178] measured weight-bearing ankle DF ROM in degrees whereas our assessment of ankle DF ROM involved a weight-bearing lunge test measured in centimeters.

Single Leg Anterior Reach

Single leg anterior reach performance did not significantly moderate the relationship between SLAR LSI and injury, indicating that any potential relationship between LSI and injury did not vary as a function of performance. Additionally, secondary analyses indicated that neither SLAR LSI nor SLAR performance were related to LE injury independent of age, sex, sport, and injury history. The lack of association between SLAR LSI and injury was contradictory to previous research performed on high school and college athletes.[17,170] The differing results may have resulted from study methodology differences. Studies suggesting SLAR asymmetry is indicative of increased injury risk were performed as a part of the Star Excursion Balance Test (SEBT),[17,170] which does not require the Lower Quarter Y-Balance Test kit that was used in our study. Researchers have demonstrated that anterior reach performance may differ between the

SEBT and Y-Balance test and therefore our findings may be a result of different test demands.[171,172]

The lack of association between SLAR performance and injury was consistent with previous research by Plisky et al.[17] Anterior reach distance on the SEBT was not associated with increased risk of injury in high school basketball players after controlling for confounding variables.[17] However, our findings are contradictory to research indicating that worse performance on the anterior direction of the Lower Quarter Y-Balance Test increases risk of LE injury.[16,19] These contradictory findings may be explained by differences in study populations and injury definitions. Butler et al.[16] studied risk of non-contact LE injury in college football players and Gribble et al.[19] studied risk of lateral ankle sprains in high school and college football players.

Single Leg Hop for Distance

Similar to the SLAR findings, SLHOP performance did not significantly moderate the relationship between SLHOP LSI and injury. Additionally, secondary analyses indicated that neither SLHOP LSI nor SLHOP performance were related to LE injury independent of age, sex, sport, and injury history. These findings are consistent with previous research findings that suggested SLHOP performance was not associated with risk of injury in female soccer players.[63] However, our findings differ from those of Brumitt et al.[22] who identified that the odds of injury was greater among females with SLHOP asymmetries greater than 10%. Brumitt et al. also identified that makes with SLHOP distances less than 75% of their height were more likely to suffer an injury.[22]

This study was performed in division III college athletes however, potentially explaining the outcome differences.

Injury History

Injury history was associated with LE MSK injury following confirmatory data analysis. Odds of sustaining a LE MSK injury were twice as likely among patients who reported sustaining a previous injury. This finding is consistent with research across a variety of study populations.[8,9,67,173] Individuals with a history of ankle sprains are more likely to sustain a future ankle sprain than individuals with no prior ankle sprains.[67] Similarly, individuals with a previous ACL injury are more likely to suffer a future ACL injury than individuals with no prior ACL injury.[173] The association between previous and future injury may be due to residual mobility, postural control, or strength impairments following initial injury. Schmitt et al. demonstrated that quadriceps strength deficits following ACL reconstruction negatively influence function and hop test performance.[174] These impairments, if not properly rehabilitated, may persist, increasing future injury risk. These findings highlight the need for accurate injury history reporting during PPEs in order to identify individuals who need further medical evaluation to mitigate future injury risk.

Age

Age was significantly related to LE MSK injury in the confirmatory analysis, although this relationship was small. Specifically, the odds of injury increase as age increases. This finding is consistent with previous research among youth football players[179] and may be indicative of greater size and speed of older individuals. This finding may also be explained by activity level. Hootman et al. identified that the odds of injury increases as activity level increases.[180] Older individuals may be playing in more games, therefore placing themselves at risk of injury more often.

Limitations

Results from this study are based on soccer and basketball athletes, and therefore cannot be generalized to other high school sports. Since we only included high school athletes we cannot generalize our results to soccer and basketball athletes of other competition levels (e.g. youth, college). Also, by including time loss injuries only our results don't reflect moderated effects of non-time loss LE MSK injuries. We also did not differentiate between acute and overuse injuries. Functional performance was assessed during the pre-season and may not reflect athletes' functional performance prior to injury if that injury occurred late in the season. The inability of functional performance to predict injury may therefore be explained by the time in season that injury occurred. It is important to note that we did not record athlete-exposures, such as numbers of games and practices participated in, due to our concern with our ability to accurately capture exposure data. Lastly, injury history was self-reported and thus possibly underreported.

CONCLUSION

Identifying moderators of LE MSK injury in adolescent athletes may help clinicians better identify individuals at an increased risk of injury who would benefit the most from injury prevention interventions. This study indicates that effects of ankle DF ROM LSI, SLAR LSI, and SLHOP LSI on injury may not be moderated by ankle DF

ROM performance, SLAR performance, and SLHOP performance, respectively. Additionally, functional performances and functional asymmetries may not be directly related to injury independent of age, sex, sport, and injury history. Additional functional performance tests, as well as more sensitive measures of functional performance, should be evaluated in an attempt to better identify individuals at increased risk of injury. Injury history was directly related to an increased likelihood of future injury. This finding highlights the need to obtain accurate injury history to identify individuals requiring further medical evaluation to mitigate time loss LE MSK injury risk.

Chapter 6: Conclusions and Future Research Directions

CONCLUSIONS

The overall objective of this research was to assess the complex multifactorial nature of lower extremity (LE) musculoskeletal (MSK) injury in high school athletes. The rationale behind the proposed research was that establishing a clearer understanding of injury risk would ultimately lead to the development of a gold standard for assessing injury risk, and subsequently improving injury risk prediction and prevention efforts. The major findings from this study suggest that functional performance may not be related to LE injury through direct, indirect, or moderated effects. A primary risk factor for injury may be previous injury, highlighting the need for recording accurate injury history during the pre-participation physical evaluation (PPE) process to mitigate risk of injury during sport participation.

Chapter 3 established similarities and differences in epidemiology of injury in boys' and girls' high school soccer and basketball using a national injury surveillance system. The results of this chapter indicate that injury rates are greater in soccer than basketball, and greater in competitions than practices, regardless of sex. The most common injuries were similar between sports, suggesting both sports should emphasize preventing sprains and strains affecting the ankle and knee, specifically those resulting from player contact and noncontact mechanisms. Additional efforts are also needed to prevent hip and thigh/upper leg injuries in soccer. These findings may help inform the development of sport-specific injury prevention programs for soccer and basketball athletes.

Chapter 4 evaluated direct and indirect effects of functional performance asymmetries, as well as drop landing mechanics, on injury. Results from this chapter indicate that ankle dorsiflexion (DF) range of motion (ROM) limb symmetry index (LSI), single leg anterior reach (SLAR) LSI, anterior single leg hop for distance (SLHOP) LSI, and Impression Landing Error Scoring System (iLESS) performance are neither directly nor indirectly related to odds of LE MSK injury in high school soccer and basketball players. Injury history was directly related to an increased likelihood of future injury.

Chapter 5 evaluated whether potential relationships between functional asymmetries and LE injury were moderated by functional performance. Results from this chapter indicate that effects of ankle DF ROM LSI, SLAR LSI, and SLHOP LSI on injury may not be moderated by ankle DF ROM performance, SLAR performance, and SLHOP performance, respectively. Additionally, functional performances may not be directly related to injury independent of functional asymmetries, age, sex, sport, and injury history. As was identified in Chapter 4, injury history was directly related to an increased likelihood of future injury. Findings from chapters 4 and 5 suggest that additional functional performance tests, as well as more sensitive measures of functional performance, should be evaluated in an attempt to better identify individuals at increased risk of injury. The statistically significant relationship between previous injury and future injury highlights the need to obtain accurate injury history during PPEs to identify individuals requiring further medical evaluation to mitigate time loss LE MSK injury risk.

FUTURE RESEARCH DIRECTIONS

Future research directions will focus on the steps necessary to achieve our long term goal of identifying individuals at greater risk of injury who would therefore benefit the most from injury prevention interventions. To achieve this goal, future research will evaluate the ability for different functional tests to identify risk of injury in high school athletes. This research will use sport-specific tests to better identify intrinsic risk factors that are relevant to those sports. Future research will also be performed to develop an understanding of risk factors for joint specific injuries (e.g. ankle injury, knee injury, or thigh injury). More sensitive measures of human movement will be studied to identify if improving measurement sensitivity improves predictive ability of functional testing. Examples of more sensitive assessments include kinematic assessments using inertial measurement units or kinetic assessments using portable force plates. Future research will also include measures of risk taking behaviors in the injury process to better reflect psychological influences on injury.

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