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Examination of Lower Extremity Mechanics During Three Landing Tasks and Injury Prediction
Ability of Those Models as Compared to a Functional Test

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of
Philosophy at Virginia Commonwealth University

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List of Abbreviations

ACL	=	Anterior cruciate ligament
AHDL	=	Adjust height drop landing
DL	=	Drop landing
F8	=	Figure 8 hop task
FAT	=	Functional Ability Test
FIN	=	Femoral intercondylar notch
GRF	=	Ground reaction force
HADi	=	Hip adduction at impact
HADm	=	Hip adduction maximum
HD	=	Single hop distance task
KAi	=	Knee abduction angle at impact
KAm	=	Maximum knee abduction angle
KFi	=	Knee flexion angle at impact
KFm	=	Maximum knee flexion angle
KIRi	=	Internal knee rotation angle at impact
KIRm	=	Maximum internal knee rotation angle
LESS	=	Landing Error Scoring System
LR	=	Loading rate
NNT	=	Numbers Needed to Treat
OA	=	Osteoarthritis
SH	=	Side hop task
UD	=	Up and down hop task
VJL	=	Vertical jump landing

Abstract

Examination of Lower Extremity Mechanics During Three Landing Tasks and Injury Prediction Ability of Those Models as Compared to a Functional Test

By: Timothy G. Coffey

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Virginia Commonwealth University

Virginia Commonwealth University, 2015

Major Director: Peter E. Pidcoe, PT, DPT, PhD, Associate Professor, Department of Physical Therapy

Anterior cruciate ligament (ACL) ruptures are one of the most common knee ligament injuries suffered by both male and female athletes. These injuries are severe in nature and also have long-term impacts on activities of daily living. Significant research has been conducted utilizing a drop landing task to attempt to better understand the mechanics behind the injury and to help identify at-risk athletes for targeted intervention. However, there have not been any published standards for the height of the drop landing activity, and previous researchers have also raised some concerns about the ability of a drop landing task to replicate the landing mechanics of a sport-specific task.

To examine possible differences in performance based on specific landing tasks, the first study compared the landing mechanics of male and female high school athletes in three different landing conditions (drop landing, DL; adjusted height drop landing, AHDL; and a vertical jump task, VJL) (Chapter 3). Thirty-seven (37) athletes completed bilateral landings in the three

conditions, and their kinetic and kinematic landing mechanics were compared across conditions. For the male participants, maximum knee flexion during landing was greater in AHDL condition as compared to the DL and VJL conditions. Both male and female participants demonstrated greater hip adduction at impact and overall maximum value in the VJL condition as compared to the two drop landings.

As drop landing tasks have been used to identify at-risk athletes, it was important to examine the three different tasks' ability to predict lower extremity ligamentous injuries, and whether those 3D motion analysis predictors were more precise than a quick clinical symmetry screening tool (Chapter 4). One-hundred-and-sixty-five (165) athletes completed the clinical symmetry screen, and a subgroup of thirty-seven (37) athletes completed the 3D motion analysis. All of these participants were surveyed for lower extremity ligamentous injuries over the course of a season. Due to a small number of reported injuries, none of the injury predictor models based on 3D motion analysis landing mechanics or the clinical symmetry screening tool were able to produce accurate predictor models of injury.

Knee abduction moment has been shown to be one of the strongest predictors of ACL injuries, and due to the collection of bilateral kinetics for a previous study (Chapter 3), there was a need to examine differences in KAM between the three different landing tasks (Chapter 5). Ten (10) recreational athletes completed bilateral landings in the three conditions, with foot placement relative to force plates to enable KAM calculation. The participants did not demonstrate any difference in KAM between the three landing conditions; however, a test for constant variance showed that the AHDL resulted in significantly less variance in KAM than DL or VJL.

The results of these studies suggest that while easy to standardize, a set height drop landing task does not produce identical landing mechanics to those from an adjusted height drop landing task or a vertical jump task. Further research is needed to create or justify standardized landing tasks for researchers to utilize that produce consistent results that best duplicate the landing mechanics athletes performed during sporting activities. While the landing mechanics demonstrated in the three tasks and the results from the clinical screening were not able to predict injuries, future studies should examine quick clinical screening tools to identify athletes at a high risk of injury.

Chapter 1: Introduction

Statement of the Problem

Background

The passage of Title IX in 1972, led to increased female participation in high school athletics increasing 9-fold in less than thirty years. During that same thirty year timeframe, male participation in high school athletics only increased by 3 percent (National Federation of State High School Associations, 2002). As the number of participating female athletes has risen quickly over the years, so have the number of injuries suffered by these young female athletes. A majority of the injuries affecting both male and female athletes are associated with the lower extremities, especially the ankle and the knee (Bahr & Bahr, 1997; Barker & Beynnon, 1997; Colliander, Eriksson, & Herkel, 1986; Emery, Meeuwisse, & McAllister, 2006; Garrick, 1977). The knee joint is the second most common site of injury among all athletes, surpassed only by the ankle (Bahr & Bahr, 1997; Barker & Beynnon, 1997; Colliander, Eriksson, & Herkel, 1986; Emery, Meeuwisse, & McAllister, 2006; Garrick, 1977).

While the noncontact anterior cruciate ligament (ACL) rupture rate for female athletes is significantly greater than it is for their male counterparts (Arendt, Agel, & Dick, 1999; Harmon

& Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994; Shea, Pfeiffer, Wang, Curtin, & Apel, 2004), the rupture of the ACL is one of the most common knee ligament injuries suffered by both male and female athletes (Beynnon, Johnson, Abate, Fleming, & Nichols, 2005; Ford, et al., 2006). A noncontact ACL rupture is a severe and damaging injury, and the incidence rate among male and female athletes has continued to increase in the last 10 years by almost 50 percent (Donnelly, Elliott, Ackland, & Doyle, 2012), and has increased even when compared to the rate of other sports related injuries (Sampson, et al., 2011). This incidence rate for noncontact ACL injuries has been shown to range from 2 to 8 times in terms of the risk for female athletes as compared to male athletes in the same sport (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994). It has been estimated that between 175,000 and 200,000 ACL injuries occur in just the United States every year (Myer, Ford, & Hewett, 2004; Prodromos, Han, Rogowski, Joyce, & Shi, 2007), and based on the trend of increased incidence rates (Donnelly, Elliott, Ackland, & Doyle, 2012; Sampson, et al., 2011), that number can only be expected to continue increasing. An overwhelming majority of all ACL ruptures, nearly 70 percent, can be labeled as “noncontact,” meaning there was no external contact to the knee or body that directly caused the injury to occur (Boden, Dean, Feagin, & Garrett, 2000). This suggests that these noncontact ACL injuries are related to movement and movement patterns of the injured athlete; and not to impact forces applied from another athlete or object.

An examination of the current research investigating incidence rates of noncontact ACL injuries, sports of interest, and exact gender incidence rate differences, does not provide clear and convincing evidence concerning the specific etiology of the injury. What is known and agreed upon by researchers is that female athletes participating in sports that involve “high risk

movements” sustain noncontact ACL ruptures at a rate that varies between 2 to 8 times greater than the injury rate of male athletes in the same sports (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994). These “high risk movements” include movements such as jumping, landing, pivoting and cutting tasks that are often associated with high external knee joint loads (Boden, Dean, Feagin, & Garrett, 2000; Marshall, Padua, & McGrath, 2007; Besier, Lloyd, Cochrane, & Ackland, 2001). These loads are usually the result of forced external rotation of the femur on a fixed tibia with the knee in full extension, which tends to be the most frequent mechanism of noncontact injury to the ACL among athletes (Noyes, DeLucas, & Torvik, 1974). These “high risk movements” are all commonplace in court and field sports, such as basketball, handball, soccer, lacrosse, and volleyball.

Injury Factors

Over the past 20 years, a great deal of research has been done to try to identify the factors that are involved in the large gender discrepancy in the incidence rate of noncontact ACL ruptures, but a precise illustration of the multifactorial injury has yet to be created (Arendt, Bershadsky, & Agel, 2002; Shultz, et al., 2010). In March 2010, at a recent research retreat on the observed gender bias in noncontact ACL incidence rate, a number of consensus statements were updated from previous retreats concerning what is known about factors related to noncontact ACL ruptures, as well as areas of suggested future research. Researchers have divided noncontact ACL injury factors into the three following categories: (1) anatomical and structural, (2) hormonal, and (3) neuromuscular and biomechanical (Arendt, Bershadsky, &

Agel, 2002; Shultz, et al., 2010). Due to the ability of clinicians and researchers to modify the neuromuscular and biomechanical factors, those factors have recently gained increased attention in attempting to examine the possible mechanical etiology of noncontact ACL injuries as well as identifying “at-risk” athletes (Chappell, Yu, Kirkendall, & Garrett, 2002; Hakkinen, Kraemer, & Newton, 1997; Hewett, et al., 2005; Huston, 2007; Huston & Wojtys, 1996; James, et al., 2001; Kanehisa, Okuyama, Ikegawa, & Fukunaga, 1996; Lephart, Abt, & Ferris, 2002).

Drop Landing

A popular task that has been used by researchers to help assess and examine the neuromuscular factors possibly associated with noncontact ACL injury risk is a drop landing task. Hewett et. al., (2005) investigated a number of neuromuscular factors associated with a drop landing task with the goal of being able to better predict noncontact ACL injuries in female high school athletes. Their study used 205 adolescent female athletes and prospectively measured their neuromuscular control during a drop landing task from a height of 31cm. The researchers then followed the participants to record which participants sustained noncontact ACL injury while participating in their particular sport. Out of the 205 participants, nine participants subsequently suffered non-contact ACL injuries. The injured group displayed greater knee abduction angle at landing ($P<.05$), 2.5 times greater knee abduction moment ($P<.001$), 20% greater ground reaction force ($P<.05$), and decreased stance time (16%; $P<.01$) over the length of the study. Knee abduction moments for the participants also served as an accurate predictor of ACL injury via a logistic regression, 73% of the time. The completed linear regression model,

including knee abduction moments and angles, as well as side to side differences, had an r^2 value equal to 0.88. These results led the researchers to conclude that female athletes with increased dynamic valgus at impact and high knee abduction moments were at a greater risk to sustain a noncontact ACL injury. It is presently unclear if the same neuromuscular factors can be attributed to or utilized in examining the factors associated with the incidence of noncontact ACL injuries in male athletes.

A number of other studies have utilized drop landing tasks to examine possible gender differences in lower extremity mechanics in an attempt to understand why female athletes are more susceptible to noncontact ACL injuries (Cortes, et al., 2007; Decker, Torry, Wyland, Sterett, & Steadman, 2003; Fagenbaum & Darling, 2003; Ford, et al., 2006; Huston, Vibert, Ashton-Miller, & Wojtys, 2001; Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005; Nagano, Ida, Akai, & Fukubayashi, 2007; Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007; Russell, Palmieri, Zinder, & Ingersoll, 2006). These studies have produced mixed results, with some finding significant differences for males and females in maximum knee ab/adduction angles (Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005), and knee ab/adduction and knee flexion angles at impact (Decker, Torry, Wyland, Sterett, & Steadman, 2003; Fagenbaum & Darling, 2003; Huston, Vibert, Ashton-Miller, & Wojtys, 2001). On the contrary, other studies did not find any significant differences in the lower extremity mechanics between males and females (Cortes, et al., 2007; Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007). It is unclear from the mixed results of these studies what specific lower extremity mechanics are more predominate in female athletes that may predispose them to noncontact ACL injuries. It is also unclear if the observed differences or lack of significant differences in lower extremity mechanics is actually due to gender differences in mechanics or influenced by individual differences in performance.

Male and female athletes have been shown to produce significantly different maximum vertical jump heights (Abian, Alegre, Lara, Rubio, & Aquado, 2008; Walsh, 2007), and thus landing from a set height identical for both genders, such as the ones utilized by these studies, may jeopardize the validity of the findings. It is also concerning that direct comparisons between genders, where there is a basic assumption that the mechanics demonstrated by female athletes may lead to noncontact ACL injuries, may be misleading. While female athletes are at a greater risk for noncontact ACL injury, there are still a great number of female athletes who do not suffer noncontact ACL injuries (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994). Also, while males are at less risk of a noncontact ACL rupture than female athletes, they are far from immune to suffering this injury. Thus, direct comparisons of lower extremity mechanics between males and females are complicated by possibly inaccurate assumptions of performance and incidence rates of noncontact ACL injuries.

A basic assumption by researchers utilizing drop landings is that these landing performances accurately represent landing from an athletic performance move, such as a basketball rebound or volleyball block. Drop landing, however, may be a novel task, since the activity is one typically only used in either a research study setting (Edwards, Steele, & McGhee, 2010) or a workout routine (Bobbert, 1990), and not one typically performed during normal participation in a court or field sport. One recent study examined differences in lower extremity landing mechanics between a drop landing and a volleyball spike jump landing in skilled male volleyball players (Edwards, Steele, & McGhee, 2010). While the generalizability of this study is greatly reduced by the use of a very sport specific task, sand volleyball spike jump, it does provide possible valuable insights into the use of drop landings. The results of this study illustrated that in the drop landing condition, the participants landed with greater stiffness,

exemplified by less knee flexion at impact, and greater ground reaction forces and loading rates, as compared to the spike jump condition.

A confounder to these results is that further examination of the landings suggested that the vertical displacement across subjects may not have been equal. The researchers determined that while they attempted to standardize the height of the two activities, participants during the drop landing condition exhibited greater vertical displacement as compared to the spike jump condition. Even though the researchers attempted to dismiss this difference in vertical displacement, it is possible that it could have influenced some of the observed landing mechanics. To accurately examine differences in the landing mechanics of different tasks, it may be important to standardize the height, so as to reduce possible kinetic energy differences that could impact landing mechanics. While the vertical displacement differences might have impacted the results from this study, the results still suggest that laboratory activities, such as drop landings, may not be accurately representative of an in-game activity, such as landing from a jump task (Edwards, Steele, & McGhee, 2010).

Another basic assumption of research utilizing a drop landing task is that individual differences in performance variables, such as maximum vertical jump height, are not taken into account when determining the specific height of the drop landing task (Coffey, 2010). Maximum vertical jumps, however, do vary by individual, and it may be problematic to assume that performing a 30cm drop is the same activity for an individual with a maximum vertical jump of 30cm as compared to an individual with a 61cm maximum vertical jump. Pilot data for this study found that maximum vertical jump height ranged from 30cm to 47cm for females and 43cm to 61cm for males. For a drop landing task with a height of 30cm, the female participant with the 30cm maximum vertical jump is performing a task at a height equal to 100% of her

maximum vertical jump. The other extreme is the female participant with the 47cm maximum vertical jump, who is performing the same task, but it is only at a height equal to 64% of her maximum vertical jump. While it might seem questionable when examining landing mechanics during drop landings to not take this performance difference into account, most researchers have focused on standardizing the height rather than the activity or task (Coffey, 2010).

Neuromuscular performances from a drop landing task facilitated the creation of an injury predictor model for female athletes, but the model was far from perfect with a 73% accuracy rating (Hewett, et al., 2005). This level of accuracy suggests that there may exist some concerns with the use of a drop landing task to assess neuromuscular performance associated with noncontact ACL injuries. These concerns would only be magnified when using the results from the regression predictor model as the basis for designing a functional injury screening tool, which would introduce its own variability, negatively impacting the accuracy. It may be possible that this predictor model could be strengthened with the use of a sport specific task or activity.

It has been previously reported that individuals displayed different landing mechanics when performing a sport based task (spike jump) as compared to a drop landing (Edwards, Steele, & McGhee, 2010). A spike jump, while a sport based task, is an action that is typically only observed in one sport, volleyball, and this study only examined landings for beach volleyball. A vertical jump, however, is an activity that is commonly performed in a variety of court and field sports (soccer, basketball, and volleyball), and associated with the occurrence of noncontact ACL injuries (Besier, Lloyd, Cochrane, & Ackland, 2001; Boden, Dean, Feagin, & Garrett, 2000; Marshall, Padua, & McGrath, 2007). An in-game activity, such as a vertical jump landing (VJL) task, may reproduce neuromuscular performances that more accurately represent those that occur during normal athletic participation in a variety of sports. Vertical jump

performance has been shown to vary between subjects and between genders (Abian, Alegre, Lara, Rubio, & Aquado, 2008; Walsh, 2007), and thus may need to be taken in account when assessing an individual's landing mechanics. Individual performance variability with respect to vertical jump performance is not currently taken into account by a number of studies that have utilized a set height drop landing task (Coffey, 2010), and may be an important factor on the accuracy of the observed landing mechanics to those that occur during regular athletic performances. A more accurate representation of landing mechanics should then increase the accuracy of a regression predictor model for noncontact ACL injuries. A stronger predictor model would allow for the creation of a more valid and accurate functional screening tool to identify individuals at risk of a noncontact ACL injury. A more accurate screening tool would allow for more targeting neuromuscular training interventions, thus reducing the incidence rate of noncontact ACL injuries.

Purpose of the Research

The purpose of this research study was to examine the ability of a clinical screening tool to identify athletes at risk for suffering lower extremity ligamentous injuries, including ACL injuries, and to compare that prediction ability to the injury prediction ability of three different models created utilizing 3D motion analysis data from three landing tasks, as well as comparing the observed landing mechanics during those landing tasks.

Research Aims and Hypotheses

This study has the following three specific aims:

Specific Aim 1:

Do individuals display different lower extremity landing mechanics when performing different jump/landing tasks? Do these landing mechanics also differ between clinically assessed asymmetric and symmetric individuals?

Hypothesis 1:

Differences in the kinematic and kinetic variables of interest were expected to be observed for both male and female subject groupings and between the symmetric and asymmetric subgroups for each gender for each of the three landing tasks: set height drop landing (DL), adjusted height drop landing (AHDL), and vertical jump landing (VJL). The landing mechanics between the VJL and the two drop landing tasks (AHDL and DL) were expected to be different, as the use of a novel task (drop landing) in the AHDL and DL conditions has been shown to impact performance (Edwards, Steele, & McGhee, 2010). It was also expected that the VJL and AHDL conditions would result in different landing mechanics than the DL due to a change in height of the activity based on individual performance. This

difference in height of the activity, then, has a direct impact on the potential energy level of the landing and individual responses to changes in the amount of energy absorption during landing.

A previous study (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998) determined that demonstrated asymmetry during these four single limb hopping tasks equated to decreased dynamic stability and identification as ACL deficient. Based upon these results, it was theorized that clinically assessed asymmetric individuals as compared to clinically assessed symmetric individuals would display landing mechanics possibly associated with noncontact ACL injuries, including increased knee abduction angle at impact and increased ground reaction force (Hewett, et al., 2005).

Specific Aim 2:

Do clinically assessed asymmetric individuals display a greater relative risk for lower extremity ligamentous injury as compared to clinically assessed symmetric individuals? Does the type of landing task affect the ability of lower extremity landing mechanics to predict occurrences of lower extremity ligamentous injury? Are any of these task based predictions stronger than a prediction based on symmetry/asymmetry?

Hypothesis 2:

It was expected that the clinically assessed asymmetric individuals would display greater relative risk for lower extremity ligamentous injury than those subjects clinically assessed as

symmetric. A previous single limb hop test study (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998) found these four single limb hopping tasks allowed for the identification of decreased dynamic stability and ACL deficiency. Based upon these results, it was theorized that clinically assessed asymmetric individuals as compared to clinically assessed symmetric individuals would display decreased dynamic stability which may be directly related to the risk of ACL injury (Ford, Myer, & Hewett, 2007) and possibly other lower extremity ligamentous injuries.

It was expected that among the three injury-prediction models created using 3D motion analysis data for each of the landing tasks, the ability to predict injury incidents would be the greatest for the VJL task. It was theorized that because the VJL was the only task that is not a novel one and incorporates individual performance, it would provide the greatest insight into injury risk. The AHDL task was expected to be less accurate than the VJL, but more accurate than the DL, as it incorporates individual performance differences into the task while still utilizing a novel task (drop landing) which has been shown to impact performance (Edwards, Steele, & McGhee, 2010).

It was expected that the injury predictor models created from the 3D motion analysis data of the three landing tasks would display greater strength than the predictor model created by the clinical symmetry/asymmetry assessment. It was theorized that the increased specificity in the kinetic and kinematic measures from the 3D motion analysis as compared to the clinical assessment (Myer, Ford, & Hewett, 2006) would provide a more accurate injury prediction model.

Specific Aim 3:

Do individuals display different knee abduction moments when performing different jump/landing tasks? Do these knee abduction moments also differ between clinically assessed asymmetric and symmetric individuals?

Hypothesis 3:

Differences in the knee abduction moments for the right and left side were expected to be observed for the participants and between the symmetric and asymmetric subgroups for each of the three landing tasks: set height drop landing (DL), adjusted height drop landing (AHDL), and vertical jump landing (VJL). The knee abduction moments between the VJL and the two drop landing tasks (AHDL and DL) were expected to be different, as the use of a novel task (drop landing) in the AHDL and DL conditions has been shown to impact performance (Edwards, Steele, & McGhee, 2010). It was also expected that the VJL and AHDL conditions would result in different knee abduction moments than the DL due to a change in height of the activity based on individual performance. This difference in height of the activity, then, has a direct impact on the potential energy level of the landing and individual responses to changes in the amount of energy absorption during landing.

A previous study (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998) determined that demonstrated asymmetry during these four single limb hopping tasks equated to decreased dynamic stability and identification as ACL deficient. Based upon these results, it was theorized that clinically assessed asymmetric individuals as compared to clinically assessed symmetric

individuals would display landing mechanics possibly associated with noncontact ACL injuries, including increased knee abduction moment (Hewett, et al., 2005).

Participant Annotation:

This line of research utilized a variety of different participant groupings and a subgrouping, depending upon the specific aim being addressed. To help the reader understand the different groupings, visual graphics of the participants by specific aim are shown below in Figures 1-3.

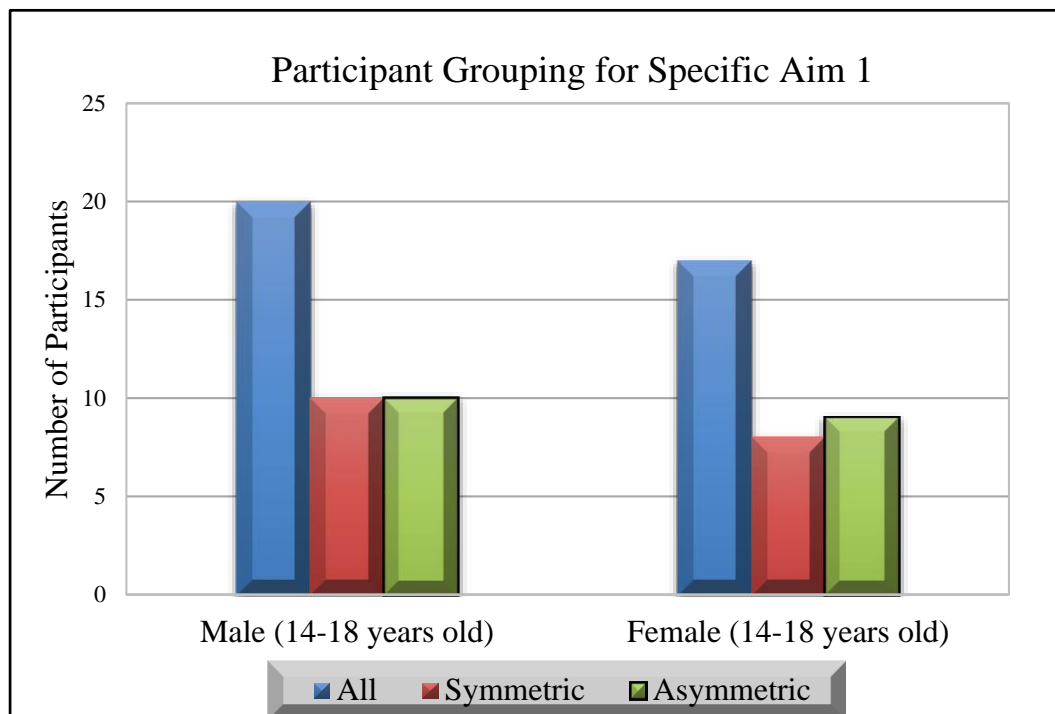


Figure 1. Graphical representation of participant grouping for Specific Aim 1.

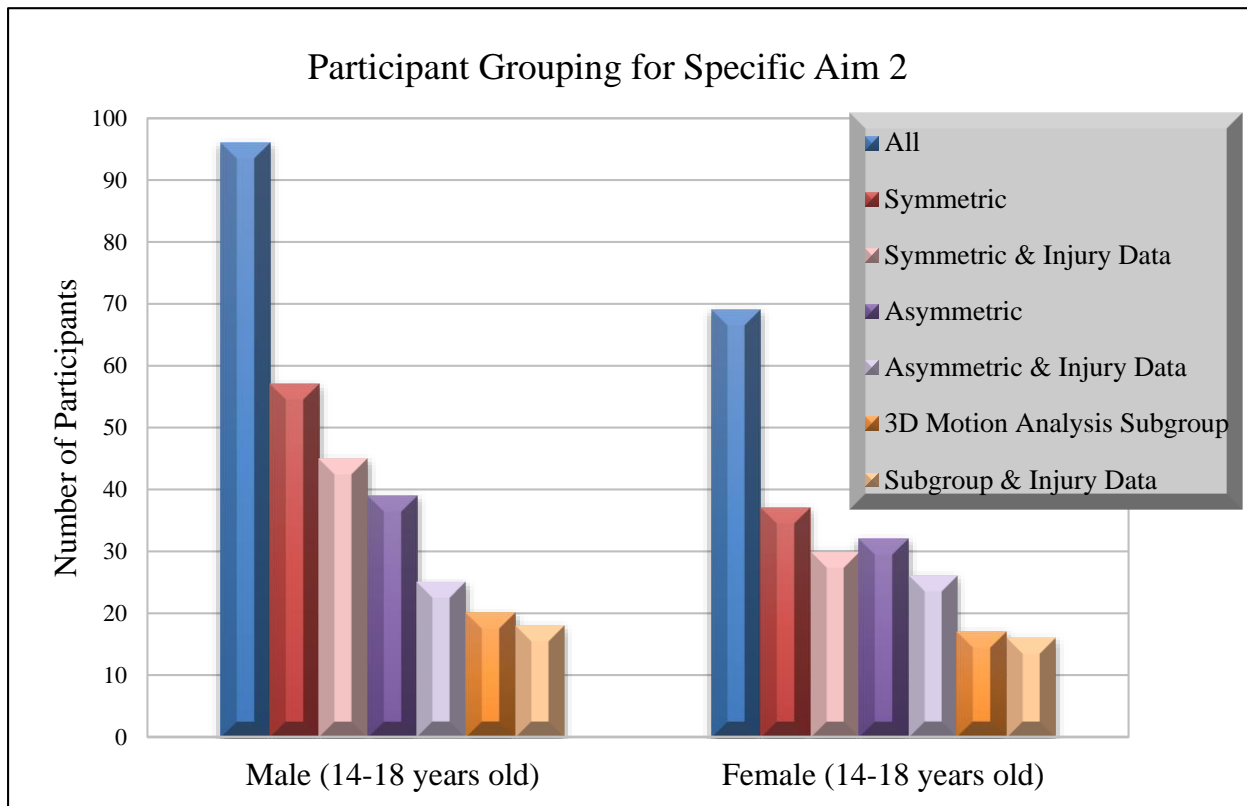


Figure 2. Graphical representation of participant grouping for Specific Aim 2.

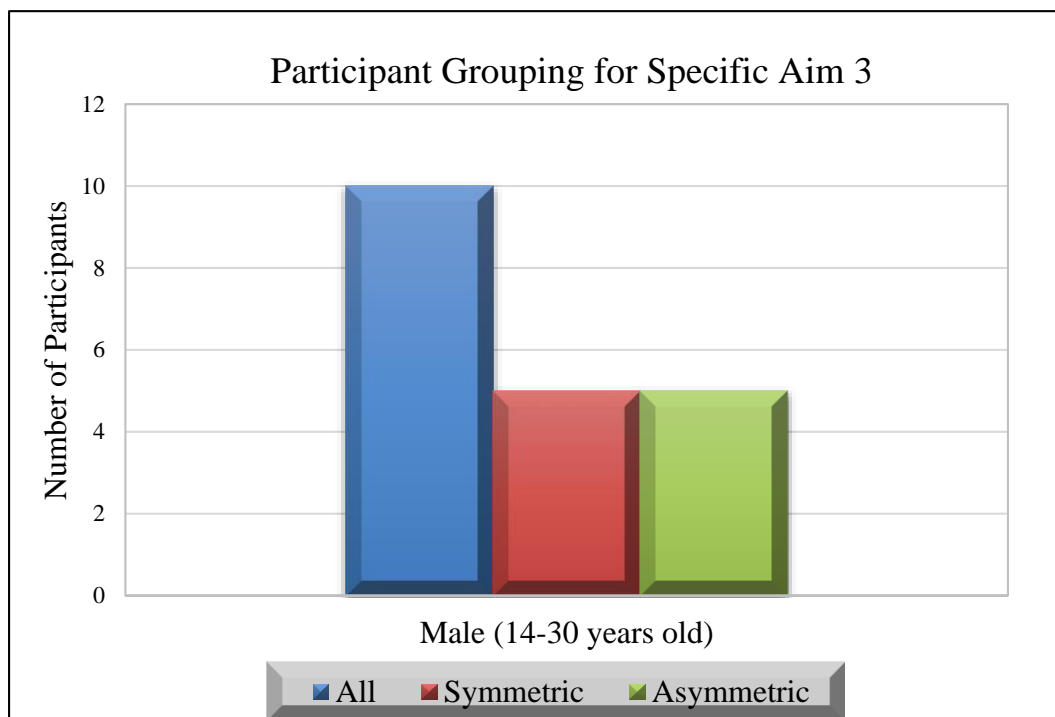


Figure 3. Graphical representation of participant grouping for Specific Aim 3.

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Chapter Two: Literature Review

Background

Since Title IX was passed in 1972, female participation in high school athletics has increased substantially (National Federation of State High School Associations, 2002), and unfortunately the incidence rate of female anterior cruciate ligament (ACL) injuries has also increased significantly (Shultz, et al., 2010), especially in the last 10 years (Donnelly, Elliott, Ackland, & Doyle, 2012; Sampson, et al., 2011). Injury research has suggested that there is a substantial gender difference in the incidence rate for noncontact ACL injuries, with the rates for female athletes being 2 to 8 times that of their male counterparts (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994). Researchers have estimated that annually 175,000 to 200,000 ACL ruptures are suffered just in the United States (Myer, Ford, & Hewett, 2004; Prodromos, Han, Rogowski, Joyce, & Shi, 2007), and based upon recent injury trends, that number is only going to continue increasing (Donnelly, Elliott, Ackland, & Doyle, 2012; Sampson, et al., 2011). An overwhelming majority - 70 percent - of these ACL injuries can be categorized as “noncontact,” suggesting that there was no external contact or force causing the injury, but rather that the injury was caused as a result of internal loading on the ACL at a load greater than the ligament could resist (Boden, Dean, Feagin, & Garrett, 2000).

The financial costs attributed to an ACL rupture can be quite steep, including surgery, rehabilitation, and long-term care for secondary knee joint injuries. The average cost of surgical management and post-operative rehabilitation for an athlete with an ACL injury has been estimated to be approximately \$17,000 (Huston, Greenfield, & Wojtys, 2000). For high school and collegiate female athletes in the United States alone, the medical expenditures for ACL injuries have been estimated to be approximately 646 million dollars annually (Huston, Greenfield, & Wojtys, 2000). When extrapolating from other cost studies and world population estimates, this suggested that approximately \$1 billion is spent annually in the United States on ACL injury management (Donnelly, Lloyd, Elliott, & Reinbolt, 2012). These estimated costs do not include any of the costs associated with the management or treatment of secondary knee joint injuries or disorders.

The development of knee osteoarthritis (OA), a degenerative joint disorder, has also been associated with prior ACL injuries (Lebel, et al., 2008; Lohmander, Ostenberg, Englund, & Roos, 2004; Shelbourne & Gray, 2009). One long-term follow-up study uncovered that a knee which had undergone an ACL reconstruction had a 3-fold greater prevalence for developing OA than the contralateral knee (Barenius, et al., 2014). OA is a debilitating disorder that can result in the impairment of daily activities and independence of affected individuals (Creamer & Hochberg, 1997), thus suggesting that the implications of ACL injuries can have long term health impacts on individuals. The immediate impacts of an ACL injury, combined with the financial costs and long term health implications, all illustrate the overall severity of the injury and the importance of understanding the etiology of a noncontact ACL injury.

Unfortunately, even though a great deal of research has been done examining noncontact ACL injuries and the gender disparity in incidence rate, the exact etiology of noncontact ACL

injuries and an understanding of why female athletes are at greater risk remains unknown (Shultz, et al., 2010). While the specific etiology of noncontact ACL injuries is not known, a considerable knowledge base has been gained and researchers continue examining the multifactorial conundrum of noncontact ACL injuries and the gender disparity in the incidence rates. The purpose of this section is to review what is known in the following areas: (1) epidemiology of noncontact ACL injuries, (2) mechanics and pathomechanics associated with noncontact ACL injuries, and (3) prevention and interventions strategies for reducing noncontact ACL injury risk.

Epidemiology of Noncontact ACL Injuries

The incidence rate for ACL injuries has been shown to be 2 to 8 times greater for female athletes as compared to male athletes in the same sport (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994). An exact incidence rate of ACL ruptures can be difficult to pinpoint due to the multiple issues that are involved with injury data collection, but a general range of incidence rates is estimated to be between 0.06 to 0.24 per 1000 exposures (hours) (Arendt & Randall, 1995; Hewett, Lindenfield, Riccobene, & Noyes, 1999; Hutchinson & Ireland, 1995; Mandelbaum, et al., 2005; Myklebust, et al., 2003; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005; Petersen, et al., 2005; Soderman, Werner, Pietila, Engstrom, & Alfredson, 2000). A sample of the confounding issues includes whether to examine the general public or just athletes, practice hours versus game hours, the exact definition of “athlete exposure,” and the notation of whether or not an ACL injury was classified as a

contact or noncontact injury. What most researchers can agree on is that when considering and examining noncontact ACL injuries, the primary sports of interest are those that require participants to regularly perform athletic maneuvers involving jumping, landing, and cutting (Marshall, Padua, & McGrath, 2007). Sports that involve the above “high risk” maneuvers include soccer, basketball, volleyball, handball, lacrosse, field hockey, and other field and court sports.

A recent meta-analysis by Prodromos et al. (2007) examined ACL injury incidence rates for multiple sports, including basketball, handball, soccer, and volleyball. ACL injury incidence rates were reviewed for all sports and calculated per 1,000 exposures. The authors of this study defined that one exposure was equal to one game or practice. Table 1 below contains the ACL injury incidence rates by sport as calculated by the authors for the 25 included studies as well as the determined ratio of female to male ACL injuries by sport. The authors were unable to calculate incidence rates for volleyball due to no ACL injuries being report in the 28,657 observed exposures. The number of reported exposures in volleyball was a much smaller number of exposures as compared to basketball (over 16,000,000), soccer (over 12,000,000), and handball (154,035). Outside of “Professional Basketball,” the ACL injury incidence rates and gender ratios from this meta-analysis are consistent with previous studies (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994), with female athletes at a much greater risk for suffering an ACL than their fellow male athletes.

Table 1. ACL injury incidence rates per 1,000 exposures for designated “high risk” sports. All rates calculated by Prodromos et al., 2007.

Sport	Female	Male	Calculated Female : Male Ratio
Indoor Soccer	5.21	1.88	2.77
Handball	0.51	0.16	3.3
Collegiate Soccer	0.32	0.12	2.67
Collegiate Basketball	0.29	0.08	3.63
Professional Basketball	0.2	0.21	0.95
High School Basketball	0.09	0.02	4.5

While the above meta-analysis has helped to provide additional information about the incidence rate of ACL injuries, it may not provide a complete and accurate answer when attempting to determine an accurate ACL injury incidence rate. One of the limitations of this analysis was that exposures for practice and games were treated as equals, which may not be completely accurate. Some studies have included the demarcation between games and practice in their methods when examining ACL injury incidence (Arendt & Randall, 1995; Arnason, Gudmundsson, Dahl, & Johannsson, 1996; Elkstrand, Gillquist, Moller, Oberg, & Liljedahl, 1983), but a majority of studies have not (Prodromos, Han, Rogowski, Joyce, & Shi, 2007). Reported incidence rate differences between game and practice exposures have ranged from 8-30 injuries per 1000 game hours and 2-5 injuries per 1000 practice hours (Arendt & Randall, 1995; Arnason, Gudmundsson, Dahl, & Johannsson, 1996; Elkstrand, Gillquist, Moller, Oberg, & Liljedahl, 1983). This may be an important difference to consider for future studies attempting to determine a more accurate and precise incidence rate for noncontact ACL ruptures, especially

when noting that a majority of noncontact ACL injuries occur during game situations (Moller & Lamb, 1997).

An examination of the current research investigating incidence rate of noncontact ACL injuries, sports of interest, and exact gender incidence rate differences does not provide an exact and clear answer for why they occur. What is known and agreed upon is that female athletes participating in sports that involve “high risk movements” sustain noncontact ACL ruptures at a rate that varies between 2 and 8 times greater than the injury rate of male athletes in the same sports (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994). These “high risk movements” include movements such as jumping, landing, pivoting and cutting tasks that are often associated with high external knee joint loads (Besier, Lloyd, Cochrane, & Ackland, 2001; Boden, Dean, Feagin, & Garrett, 2000; Marshall, Padua, & McGrath, 2007). These “high risk movements” are all commonplace in the sports of interest (basketball, handball, soccer, field hockey, lacrosse, and volleyball).

Researchers have also shown that the maturation process and the onset of puberty in athletes may also impact incidence rates of non-contact ACL injuries (Quatman, Ford, Myer, & Hewett, 2006). Studies have shown that ACL ruptures only account for 0.2% of all knee injuries for both girls and boys prior to the onset of puberty. However, for ages 11-18, ACL ruptures account for 37% and 23% of knee injuries in girls and boys, respectively (Shea, Pfeiffer, Wang, Curtin, & Apel, 2004). One recent review concluded that hormonal changes, skeletal growth, and muscle strength changes associated with puberty may impact the landing mechanics of adolescent boys and girls, and thus in turn increase their risk of a non-contact ACL rupture (Wild, Steele, & Munro, 2012). Results from the studies examining the impacts of maturation on ACL injury risk have led researchers to suggest that the optimal time to identify risk factors and

to implement neuromuscular interventions to reduce risk is during adolescence (Shultz, et al., 2010).

Mechanics and Pathomechanics of Injury

Forced external rotation of the femur on a fixed tibia with the knee in full extension tends to be the most frequent mechanism of noncontact injury to the ACL among athletes. This mechanism has been shown to produce loads on the ACL of up to 1700 N, which is large enough to cause a complete tear of the ACL (Noyes, DeLucas, & Torvik, 1974; Noyes & Grood, 1976; Smith, 1954; Trent, Walker, & Wolf, 1976). It appears that for a majority of the noncontact ACL ruptures, this forced external rotation is a result of a physical movement involving deceleration, lateral pivoting, and/or landing, which are typical in athletic tasks including jumping, landing, cutting, and pivoting (Besier, Lloyd, Cochrane, & Ackland, 2001; Boden, Dean, Feagin, & Garrett, 2000; Marshall, Padua, & McGrath, 2007). While studies have shown that the knee joint loads can be higher during these activities for both males and females, it remains unclear why jumping, landing, cutting, and pivoting maneuvers result in a greater incidence of ACL ruptures for female athletes as compared to male athletes (Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994).

Over the past 20 years, a great deal of research has focused on attempting to identify the factors that are involved in the large gender discrepancy in the incidence of ACL ruptures, but a precise depiction of those factors has yet to be created (Arendt, Bershadsky, & Agel, 2002; Shultz, et al., 2010). Recently, a number of consensus statements were created or updated by researchers concerning what is known about factors related to ACL ruptures, as well as areas of

suggested future research. Researchers divided ACL injury factors into the three following categories: (1) Anatomical and Structural, (2) Hormonal, and (3) Neuromuscular and Biomechanical (Shultz, et al., 2010). Each of those categories is quite broad, and information concerning some of the specific factors within each is described in the sections below.

Anatomical and Structural Factors

Anatomical and structural factors that have been examined include factors such as hip anteversion (Nguyen & Shultz, 2007), tibiofemoral angle (Horton & Hall, 1989; Hungerford & Barry, 1979; Hvid, Anderson, & Schmidt, 1981; McLean, Neal, Myers, & Walters, 1999; Moller & Lamb, 1997; Nguyen & Shultz, 2007; Shambaugh, Klein, & Herbert, 1991), tibial torsion (Nguyen & Shultz, 2007), genu recurvatum (Nguyen & Shultz, 2007; Trimble, Bishop, Buckley, Fields, & Rozea, 2002), quadriceps femoris angle (Q angle) (Horton & Hall, 1989; Huston, Greenfield, & Wojtys, 2000; Hvid, Anderson, & Schmidt, 1981; Nguyen & Shultz, 2007), femoral intercondylar notch geometry (Chandrashekar, Slauterbeck, & Hashemi, 2005), joint laxity (Grana & Moretz, 1978; Huston & Wojtys, 1996; Hutchinson & Ireland, 1995; Rosene & Fogarty, 1999; Scerpella, Stayer, & Makhuli, 2005), as well the mechanical properties associated with the ACL (Chandrashekar, Mansouri, Slauterbeck, & Hashemi, 2006; Chandrashekar, Slauterbeck, & Hashemi, 2005). A typical examination of these factors has included comparisons of observed differences for a multitude of variables between males and females.

One of the concerns with this approach is that while gender differences have been observed, not all female athletes sustain ACL injuries and not all male athletes are immune to them. This can lead to a misrepresentation or misunderstanding of the findings resulting from a tendency to generalize all female athletes, but a majority of those athletes do not suffer ACL ruptures. Future studies would be better served by examining the anatomical structural factors associated with gender differences in the context of a longitudinal study, allowing for long-term follow up with athletes and their injuries. When designing these future studies, an understanding of the possible anatomical and structural factors is vital.

A contributing factor to the overall stability of the knee is the structure and mechanical alignment of the pelvis, femur, and tibia. While the knee is the site of the ACL injury, the lower limb is a linked segment with a loading pattern that is modulated by the proximally (hip) and distally (ankle) adjacent joints, as well as surrounding muscles and ligaments. Past studies have shown that females, as compared to males, display increased anterior pelvic tilt, hip anteversion, tibiofemoral angle, and genu recurvatum (Nguyen & Shultz, 2007). These observed structural differences between males and females may influence the loading of the knee joint. While the altered loading of the knee joint may place the ACL at greater risk for rupture, pinpointing a direct relationship between the observed alignment differences and ACL injury may be difficult to identify. While a direct relationship between gender and ACL injury cannot be proven based upon gender-difference studies, it is possible that the observed alignment differences could affect the lower extremity mechanics and loading pattern of the knee and ACL.

Another anatomical difference that has been thought to pose a risk for an ACL rupture is the Q angle (Huston, Greenfield, & Wojtys, 2000; Nguyen & Shultz, 2007). The Q angles for males and females without a history of lower extremity injuries have been reported to range from

8° to 17° (Horton & Hall, 1989; Hvid, Anderson, & Schmidt, 1981), with the female participants consistently having greater Q angles than males. The average Q angles for males and females have been reported to be 10° and 14°, respectively (Horton & Hall, 1989; Hvid, Anderson, & Schmidt, 1981). These anatomical differences may result in the proximal reference point being more lateral in females than males (Woodland & Francis, 1992), thus creating a different loading pattern through the knee joint. Greater Q angles are also believed to increase the lateral force produced by the quadriceps femoris on the patella, thus placing additional medial stress on the knee (Shambaugh, Klein, & Herbert, 1991). This increased medial stress and altered loading pattern has been shown to increase the likelihood of the knee joint suffering an injury (Shambaugh, Klein, & Herbert, 1991; Woodland & Francis, 1992).

A structural factor that has been suggested as a possible impactor on the incidence rate of ACL ruptures is the width of an individual's femoral intercondylar notch (FIN) (Lund-Hanssen, Gannon, Holen, Anda, & Vatten, 1994; Muneta, Takakuda, & Yamamoto, 1997; Shelbourne, Davis, & Klootwyk, 1998). It has been proposed that a narrow FIN may alter the physical structure of the ACL and be a predictive factor for ACL ruptures (Muneta, Takakuda, & Yamamoto, 1997). Researchers have attempted to support a relationship between ACL injuries and small FIN widths, arguing that smaller notches result in smaller and weaker ACLs (Lund-Hanssen, Gannon, Holen, Anda, & Vatten, 1994; Shelbourne, Davis, & Klootwyk, 1998). One study examining this relationship between FIN and ACL injuries utilized radiographs from 20 female handball players who had previously suffered an ACL rupture and 26 control participants who had not suffered an injury (Lund-Hanssen, Gannon, Holen, Anda, & Vatten, 1994). They concluded based upon their findings that there was an increased risk of ACL injury associated with a decreased FIN width. A more recent cadaver study, however, concluded that there did not

appear to exist any significant gender differences in relation to the geometry of the FIN, suggesting the need for additional studies to clarify any relationship between FIN size and ACL injury susceptibility (Chandrashekar, Slauterbeck, & Hashemi, 2005).

Joint laxity, both overall and specifically within the knee joint, is another anatomical and structural factor that has been proposed as a possible component of the observed gender difference in the rate of ACL injuries. A gender difference has been shown in relation to the degree of overall joint laxity present, with females displaying a greater amount of joint laxity as compared to males (Grana & Moretz, 1978; Huston & Wojtys, 1996; Hutchinson & Ireland, 1995; Rosene & Fogarty, 1999; Scerpella, Stayer, & Makhuli, 2005). The relationship between joint laxity and injury occurrence, however, is not as clearly understood at this time. Investigators have attempted to relate the degree of joint laxity to the rate of ligament injuries with minimal success (Huston, Greenfield, & Wojtys, 2000; Rosene & Fogarty, 1999; Scerpella, Stayer, & Makhuli, 2005). One study concluded that researchers could not demonstrate that a causal relationship existed between joint laxity and the rate of ligament injuries. It was theorized by the researchers that the effects of excessive joint laxity, such as injury susceptibility, may possibly have been counteracted by the individual's strengthening the muscles around the joints displaying increased laxity (Huston, Greenfield, & Wojtys, 2000). A further examination of possible positive muscle strengthening outcomes is also covered in a later section of this work describing the efforts of neuromuscular training interventions to help reduce noncontact ACL injury rates.

While the structure around the ACL may be related to a noncontact ACL injury mechanism, another important factor to evaluate is the mechanical properties of the ACL itself. ACLs exist as two bundles of fibers which are positioned in such a fashion to provide as much

functional support as possible throughout a range of knee positions (Arnoczky, 1983). While the structural arrangement of the ACL does not differ between genders, this does not prevent the mechanical properties or the structural compositions of the ACL to differ between males and females (Chandrashekar, Mansouri, Slauterbeck, & Hashemi, 2006; Chandrashekar, Slauterbeck, & Hashemi, 2005; Hashemi, Chandrashekar, Mansouri, Slauterbeck, & Hardy, 2008). Studies have shown that the female ACL as compared to male ACLs, even after adjusting for anthropometric differences, tends to be shorter, with decreased cross-sectional area and volume (Chandrashekar, Slauterbeck, & Hashemi, 2005).

The composition of fibers within the ACL may also differ between genders, as has been shown with differences in fibril concentration and percent of area occupied by collagen fibrils. Both of these variables were significantly lower in ACL tissue samples from females as compared to the samples tested from males (Hashemi, Chandrashekar, Mansouri, Slauterbeck, & Hardy, 2008). These structural and compositional differences may also be related to observed differences in ACL mechanical properties between genders. A cadaver-based study concluded that female ACLs had a lower modulus of elasticity, and thus were less stiff, suggesting that they may not be able to prevent dangerous knee movements such as those believed to be associated with ACL ruptures (Chandrashekar, Mansouri, Slauterbeck, & Hashemi, 2006). The same study also concluded that the female ACLs failed at lower mechanical loads as compared to the male ACLs that were tested. These ACL mechanical property relationships were shown to still exist, even after the researchers adjusted for anthropomorphic differences between genders.

While a number of structural and anatomical differences between males and females have been observed in relation to ACL injuries, little evidence has suggested any direct causal relationship to noncontact ACL injury incidences. Further investigation is needed to examine

possible impacts of these structural and mechanical differences on neuromuscular outcomes, as this may provide more direct evidence concerning a relationship with ACL injury incidences. Additional research is also needed to expand the minutia of data concerning anatomical and structural changes with maturation (Arendt, Agel, & Dick, 1999; Shultz, Nguyen, & Schmitz, 2008) and how those changes may differ between males and females, impacting performance and injury risk.

Hormonal Factors

Ever since the discrepancy between female and male ACL injury rates was first observed, a great deal of attention has been given to the possible role that female hormones may play in the greater predisposition of female athletes to sustain noncontact ACL injuries (Arendt, Bershadsky, & Agel, 2002; Huston, Greenfield, & Wojtys, 2000; Wojtys, Huston, Boynton, Spindler, & Lindenfield, 2002). While numerous researchers believe that hormones may play a role in the increased incidence of ACL injuries in female athletes, the exact role or mechanism has yet to be uncovered (Arendt, Bershadsky, & Agel, 2002; Lui, Al-Shaikh, Panossian, Finerman, & Lane, 1997; Liu, Al-Shaikh, Panossian, & Yang, 1996; Slauterbeck, Narayan, Clevenger, Lundberg, & Burchfield, 1999; Wojtys, Huston, Boynton, Spindler, & Lindenfield, 2002).

One conceptual argument is that the mechanical properties of the ACL itself may be altered by changes in hormone levels within an individual, and these mechanical changes may

lead to increased ACL injury susceptibility (Dyer, Sodek, & Heershe, 1980; Hassager, Jensen, Podenphant, Riis, & Christiansen, 1990). These studies have concluded that when estrogen is introduced to collagen tissue, that tissue responds by increasing its metabolic activity, as seen by increased collagen synthesis, as well as absorption. Researchers have also discovered that there are receptor sites on the human ACL cell for estrogen and progesterone, and those researchers have suggested that these hormones could play a direct role in the composition and structure of an individual's ACL (Liu, Al-Shaikh, Panossian, & Yang, 1996). These findings could not however directly elucidate how the hormones created mechanical changes, the magnitude of any change, and if those alterations were directly related to ACL injury susceptibility.

Other researchers have reported a reduction in the tensile properties of a rabbit ACL when it was subjected to increased levels of estrogen, and argued that the decrease in tensile properties of the ACL would allow for it to be more susceptible to injury (Slauterbeck, Narayan, Clevenger, Lundberg, & Burchfield, 1999). These findings, however, have not been demonstrated in humans and may not be directly applicable to the human ACL, as mechanical property changes due to hormones may differ between species (rabbit versus human).

Based on the conclusions that possible mechanical changes of the ACL occur with changes in hormone levels, researchers have attempted to examine the relationship of the menstrual cycle with incidence rates of ACL injuries in female athletes (Arendt, Bershadsky, & Agel, 2002; Moller-Nielsen & Hammar, 1989; Moller-Nielsen & Hammar, 1991; Myklebust, Maehlum, Engebretsen, Strand, & Solheim, 1997; Slauterbeck, et al., 2002; Slauterbeck, Narayan, Clevenger, Lundberg, & Burchfield, 1999; Wojtys, Huston, Boynton, Spindler, & Lindenfield, 2002). These studies have concluded that the hormone fluctuations associated with the menstrual cycle do appear to predispose the female athlete to an ACL injury (Moller-Nielsen

& Hammar, 1991; Moller-Nielsen & Hammar, 1989; Myklebust, Maehlum, Engebretsen, Strand, & Solheim, 1997; Slauterbeck, et al., 2002), but many of the specifics are still left unanswered. Additional researchers have also reported a relationship between the timing of a female athlete's menstrual cycle and the occurrence of a noncontact ACL injury (Wojtys, Huston, Lindenfield, Hewett, & Greenfield, 1998). In this study, the investigators issued a questionnaire that was given to female athletes who had suffered a non-contact ACL injury to help determine the phase of the athlete's menstrual cycle when the ACL injury occurred. The results of the questionnaire indicated that a majority of the injuries occurred during the ovulatory phase of the menstrual cycle, which is accompanied by a surge in estrogen levels. Based upon these results, the researchers concluded that there may be a relationship between the menstrual cycle and the occurrence of noncontact ACL injuries in female athletes.

In context with the conclusions of previous researchers, it is plausible that a relationship might exist between menstrual cycle phase and ACL injuries in female athletes (Slauterbeck, Narayan, Clevenger, Lundberg, & Burchfield, 1999; Wojtys, Huston, Lindenfield, Hewett, & Greenfield, 1998). Additional follow-up research has shown that the risk of suffering an ACL injury varies with the different menstrual stages (Arendt, Bershadsky, & Agel, 2002; Wojtys, Huston, Boynton, Spindler, & Lindenfield, 2002). This research has suggested that the greatest risk of injury for female athletes has been observed during the preovulatory stage (Arendt, Bershadsky, & Agel, 2002; Wojtys, Huston, Boynton, Spindler, & Lindenfield, 2002), which varies slightly from previous results (Wojtys, Huston, Lindenfield, Hewett, & Greenfield, 1998). The preovulatory phase of the menstrual cycle does consist of dramatic shifts in hormone levels, with a significant increase just before the ovulatory phase (Larsen, Kronenberg, Melmed, & Plonsky, 2003). While the preovulatory phase may coincide with a greater risk of injury, the

research has shown that noncontact ACL ruptures can occur during any of the menstrual phases (Arendt, Bershadsky, & Agel, 2002; Wojtys, Huston, Boynton, Spindler, & Lindenfield, 2002). It is also important to note before making rash decisions concerning an individual's athletic participation to reduce injury risk based on their menstrual cycle, substantial individual variability does exist across the menstrual cycle for both hormone levels and joint laxity (Shultz, Gansneder, Sander, Kirk, & Perin, 2006), complicating any conclusions on the relationship between menstrual cycle and ACL injury susceptibility.

The exact role of hormonal changes and the impact of the menstrual cycle in relation to ACL injury incidences for female athletes have yet to be determined. What is known is that ACL injury rates have not been reported to be the same throughout the menstrual cycle, suggesting that the fluctuations in hormone levels plays at least a part in noncontact ACL injury incidences (Arendt, Bershadsky, & Agel, 2002; Wojtys, Huston, Boynton, Spindler, & Lindenfield, 2002). It is also recognized that sex hormones such as estrogen appear to have impacts on the structure of collagen tissues within the body (Dyer, Sodek, & Heershe, 1980; Hassager, Jensen, Podenphant, Riis, & Christiansen, 1990). The impact of these hormones directly on the ACL has yet to be determined, but researchers have shown that receptors do exist on the ACL for sex hormones (Liu, Al-Shaikh, Panossian, & Yang, 1996), suggesting that there may exist some impact. Additional research is needed in this area to clarify the exact nature and mechanism of the interaction of sex hormones with the ACL structure, and those impacts on ACL injury susceptibility.

Neuromuscular and Biomechanical Factors

Recently, the neuromuscular and biomechanical factors have gained increased attention by researchers examining the possible mechanical etiology of noncontact ACL injuries (Hewett, et al., 2005; Huston, 2007; James, et al., 2001; Lephart, Abt, & Ferris, 2002; Shin, Chaudhari, & Andriacchi, 2007; Yu & Garrett, 2007). Research has shown that during high risk activities such as jumping, landing, cutting, and pivoting, the ACL is loaded by a combination of sagittal and nonsagittal mechanisms, which makes it a rather complex movement to examine (Shin, Chaudhari, & Andriacchi, 2007; Yu & Garrett, 2007). A generalized theory among researchers is that the incidence of noncontact ACL injuries in female athletes may be due to poor neuromuscular control of the knee, hip, and/or ankle during an active movement, resulting in augmented sagittal and nonsagittal loading mechanisms (Huston, 2007). The primary neuromuscular control factors that help provide stability to the knee and limit this loading augmentation are muscle strength and muscle activation patterns. The loading mechanisms on the ACL may also be affected by the lower extremity mechanics demonstrated when landing from a jump or making a plant and cut maneuver. Further inspection of these mechanics has gained a great deal of interest after some significant differences were found between typical male and female landing mechanics (Chappell, Yu, Kirkendall, & Garrett, 2002; Hewett, et al., 2005; Lephart, Abt, & Ferris, 2002).

Investigators have demonstrated that even when an individual's muscle strength is normalized for their body weight, females display significantly less muscle strength in the quadriceps and hamstrings than males (Griffin, Tooms, Zwagg, Bertorini, & O'Toole, 1993; Hakkinen, Kraemer, & Newton, 1997; Huston & Wojtys, 1996; Kanehisa, Okuyama, Ikegawa, &

Fukunaga, 1996; Maughan, Watson, & Weir, 1983; Miller, MacDougall, Tarnopolsky, & Sale, 1993). These muscles surrounding the knee help to protect the knee joint from injurious loads, especially to the ACL. The observed gender difference in the strength of quadriceps and hamstrings could possibly predispose female athletes to a greater risk for injury, but this causal relationship has not been conclusively shown or supported by the research data.

Researchers have also shown that it is not uncommon for female athletes to display different muscle activation patterns for the quadriceps and hamstrings as compared to male athletes (Huston & Wojtys, 1996). One study (Huston & Wojtys, 1996) was designed to identify the possible neuromuscular factors that may predispose an athlete to knee injuries, particularly ACL ruptures in female athletes. The results of the study illustrated several gender differences, including (1) elite female athletes displayed a greater amount of anterior tibial laxity than the elite male athletes; (2) elite female athletes demonstrated significantly less muscle strength and endurance than the elite male athlete group; (3) elite female athletes used a greater amount of time to generate maximum hamstring muscle torque compared to elite male athletes; and (4) a different order of muscle recruitment was observed for the female athletes. The elite female athletes relied more on their quadriceps muscles to stabilize the knee joint in response to anterior tibial translation. The other three participant groups (elite male athletes, male non-athletes, and female non-athletes) on the other hand, relied more on their hamstring muscles for initial knee stabilization. Thus, the investigators concluded that the knee joints of male athletes are tighter (less lax) than those of female athletes. They also suggested that if the control of anterior tibial translation by the hamstrings reduces the stress placed on the ACL, then male athletes should be less susceptible to ACL injury than female athletes. The researchers did, however, acknowledge

that the neuromuscular function of the knee joints for both male and female athletes is complicated and may not be adequately appreciated or understood.

While muscle strength and activation patterns may be involved with ACL ruptures, more recent studies have centered on attempting to understand lower extremity landing mechanics and how they may relate to noncontact ACL injuries. Studies have shown that female athletes demonstrate different lower extremity mechanics than male athletes when landing from a jump, as well as when cutting and pivoting (Chappell, Yu, Kirkendall, & Garrett, 2002; Hewett, et al., 2005; Lephart, Abt, & Ferris, 2002).

One of these studies investigated some specific neuromuscular factors possibly associated ACL injuries that could be examined during a drop landing in an attempt to predict ACL injuries (Hewett, et al., 2005). This study used 205 female athletes and prospectively measured their neuromuscular control during a drop landing task, and then followed them through a sports season to observe any injuries. Nine (9) of the 205 athletes sustained a noncontact ACL injury while participating in sporting activities that season, and the findings from the study were based on data from those nine (9) subjects. The observed landing mechanics are shown in table format below in Table 3.

The researchers found that the injured group displayed greater knee abduction angle at landing ($P<.05$), 2.5 times greater knee abduction moment ($P<.001$), 20% greater ground reaction force ($P<.05$), and decreased stance time (16%; $P<.01$). Knee abduction moments for the participants also served as an accurate predictor of ACL via a logistic regression injury 73% of the time, which is fairly accurate, but needs improvement to be used realistically as a predictive measure with athletes. Using this information, researchers determined that external knee abduction loads greater than 25.25 Nm placed individuals in a high risk category for

suffering an ACL injury. These results led the researchers to conclude that female athletes that demonstrate increased dynamic valgus and high abduction loads are at a greater risk to sustain a noncontact ACL injury than those females that do not demonstrate those landing mechanic characteristics.

Table 2. Observed landing mechanic differences by subsequently injured female athletes (Hewett, et al., 2005).

Factor	Observed Differences in Injured Athletes
Knee Abduction Angle	Increased
Knee Abduction Moment	2.5 times greater
Ground Reaction Force	20% greater
Stance Time	Decreased

Drop landing studies, such as the one detailed above, that examine the neuromuscular and biomechanical factors associated with noncontact ACL injuries may provide some encouraging insights, but they are not without their shortcomings and concerns. One of those concerns is that the researchers did not provide any normalization of the utilized drop height to account for possible discrepancies in individual height or vertical jump ability. While information was not given in these studies in regards to subject vertical jump abilities, it is highly unlikely that all of the participants would have demonstrated identical vertical jump performances. This may be an especially important factor for drop landing research that is attempting to identify differences between men and women in landing performances, as it may provide insight into the difference

in ACL injury rate. A study with fifty (50) college students found an average vertical jump height of 27cm for women and 38 for men (Walsh, 2007). The observed difference between genders in vertical jump height performance confirms that individual performance differences exist and may need to be accounted for in the research design. Based on these differences, it stands to reason that taking individual performance into account when designing a research study involving a drop landing protocol is vital to ensure the validity of a study and to provide accurate information about the landing mechanics associated with noncontact ACL injuries.

The effects of fatigue on the incidence of noncontact ACL injuries has also garnered more attention as researchers have increased focus on neuromuscular and biomechanical factors associated with the injury. Research has shown that a majority of noncontact ACL ruptures occur during the second half or later stages of an athletic contest (Moller & Lamb, 1997; Price, Hawkins, Hulse, & Hodson, 2004). An early study investigating the relationship between fatigue and ACL injury examined the relationship of lower extremity fatigue on ground reaction force production, lower extremity kinematics, and muscle activation during the landing phase of a rapid run and stop (Nyland, Shapiro, Stine, Horn, & Ireland, 1994). Using Division I female basketball and volleyball players, the study showed that following fatigue, the muscle activation sequence for the knee extensor/flexor mechanism was significantly delayed. They also determined that maximum knee flexion occurred earlier during landing after being fatigued, and concluded that during fatigue, the body attempts to compensate for the mechanical properties of the knee extensor muscles. This compensation method, utilized by the extensor muscles when fatigued, could explain some of the impacts of fatigue on the landing mechanics. The researchers suggested that evidence of compensation and landing mechanic changes were

illustrated by alterations in knee kinematics and muscle activation timing following fatigue, which may interfere with an individual's ability to stabilize the knee joint in a fatigued state.

The effect of isolated fatiguing of the quadriceps and hamstrings on anterior tibial translation and muscle reaction time has also been investigated. The results of one study showed that following fatigue, the participants displayed an average increase of 32.5% in anterior tibial translation (Wojtys, Wylie, & Huston, 1996). These results also showed that the muscle responses for the gastrocnemius, hamstring, and quadriceps exhibited significant slowing and, in some cases, an absence of activity following the fatigue protocol. Researchers also found that the increases in anterior tibial translation after the quadriceps and hamstrings were fatigued strongly correlated with the delay in the response of those muscles. These two results led the researchers to conclude that fatigue may in fact play a role in the pathomechanics of knee injuries, such as noncontact ACL injuries.

While Wojtys, et al. (1996) examined the impact of fatigue on kinematics and muscle firing, others have examined the effect of fatigue on the kinetics of an individual's landing performance from a drop landing. One such study (James, et al., 2001) reported that the differences in landing performances for males as a result of being fatigued differed from those of females. On average, the female participants displayed decreased ground reaction force (GRF) magnitudes after completing a fatigue protocol, while the male participants exhibited increased GRF magnitudes after fatigue. Researchers hypothesized that the individuals who displayed an increase in GRF magnitude after being fatigued were attempting to compensate for inhibited neuromuscular control by increasing their knee joint stiffness. It was also theorized that the individuals displaying a decrease in GRF magnitudes, primarily females, were unable to adapt to the reduced neuromuscular control that resulted from being fatigued. This inability to adapt to

reduce neuromuscular control could increase an individual's susceptibility to a noncontact ACL injury.

These findings suggest that a more in-depth examination of the changes in kinematic landing performances of individuals following fatigue was warranted. A later study, examining the impacts of gender and fatigue on knee joint control strategies, supported these conclusions (Gehring, Melnyk, & Gollhofer, 2009). While using a drop landing protocol, these researchers assessed the effects of fatigue on the landing mechanics of both male and female subjects. The conclusion from the later study was that females landed with increased knee flexion velocities, increased knee joint abduction angles, and delayed activation of the lateral hamstring and medial vastus lateralis. These findings suggested that males and females utilize different neuromuscular strategies to stabilize the knee joint during landing after being fatigued (Gehring, Melnyk, & Gollhofer, 2009), but researchers were unable to draw any direct connections to ACL injury susceptibility. The relationship involving different neuromuscular strategies for males and females after fatiguing, and the corresponding possible impacts on noncontact ACL injury incidences, still needs additional research to clarify.

While a number of highly controlled laboratory studies have investigated multiple neuromuscular factors, the direct connection between these neuromuscular factors and noncontact ACL injury incidences remains unclear. A review of these studies suggests that the neuromuscular factors believed to be associated with noncontact ACL injury can be grouped into the following three areas: (1) altered movement patterns, (2) altered muscle activation patterns, and (3) inadequate or excessive muscle stiffness. A fourth interrelated factor, fatigue, also influences neuromuscular performance and may possibly be linked to noncontact ACL injury incidence.

Prevention

ACL injuries are severe and costly injuries (Huston, Greenfield, & Wojtys, 2000; Donnelly, Elliott, Ackland, & Doyle, 2012) that have been shown to possibly lead to other long term joint disorders, impacting an individual's overall quality of life (Creamer & Hochberg, 1997). While the research findings examining possible factors related to noncontact ACL injury incidences have produced some information about possible prevention, unfortunately very few strong conclusions have been produced. Even without strong conclusive findings about noncontact ACL injury factors, prevention of noncontact ACL ruptures has garnered a great deal of attention, with researchers examining neuromuscular training protocols designed to reduce the risk of noncontact ACL injury (Coffey, 2010). The development and implementation of neuromuscular training programs as an intervention has been a point of more emphasis as the search for specific anatomical, structural, and hormonal factors has been fairly unsuccessful (Silvers, Giza, & Mandelbaum, 2005). It is possible that the neuromuscular factors previously examined may be altered through interventions to reduce injury risk much easier than anatomical and hormonal factors. The specific components of these training programs have changed over time, and lack standardization concerning the activities utilized, length and duration of intervention, and frequency of intervention activity (Coffey, 2010; Grindstaff, Hammill, Tuzson, & Hertel, 2006). Even without these standardizations, these neuromuscular training programs have been shown to greatly reduce the risk of suffering an ACL injury by an average of 70% as compared to control groups (range: 48% to 100%) (Grindstaff, Hammill, Tuzson, & Hertel, 2006). It is currently unclear what the most effective components, interventions strategies, and techniques for these training programs should be (Grindstaff, Hammill, Tuzson, & Hertel, 2006;

Myer, Ford, & Hewett, 2006). Future research should focus on answering this question in order to implement the most effective neuromuscular training programs, as well as identifying the appropriate age at which to incorporate them.

Neuromuscular training programs designed to reduce the risk of noncontact ACL injury have focused on plyometrics, balance training, strength training, stretching exercises, and/or technique education to influence neuromuscular performance (Hewett, Lindenfield, Riccobene, & Noyes, 1999; Mandelbaum, et al., 2005; Myklebust, et al., 2003; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005; Petersen, et al., 2005; Soderman, Werner, Pietila, Engstrom, & Alfredson, 2000). Designers of these prevention programs argue that the observed increased neuromuscular performance is an outcome of the existing motor programs and activation patterns being remodeled by the intervention (Zebis, et al., 2008). The alteration of existing hamstring muscle motor programming has been shown to decrease the risk of dynamic valgus movement during landing, thus possibly reducing the risk of noncontact ACL injury (Zebis, et al., 2008). Improvements in muscle coordination and performance have also been demonstrated post-neuromuscular training program via clinical movement assessments such as the Landing Error Scoring System (LESS) (DiStefano, Padua, DiStefano, & Marshall, 2009). The benefits of neuromuscular training programs have been shown to be more than just injury risk reduction, but also include athletic performance improvement such as vertical jump, speed, and agility (Hewett, et al., 2005; Myer, Ford, & Hewett, 2005; Paterno, Myer, Ford, & Hewett, 2004). These results illustrating improved athletic performance as an outcome of these programs are vital in a justification to athletic coaches considering implementation of an intervention program supplementing or replacing an existing time constrained training, warm-up, and/or practice schedule.

Within these neuromuscular training programs, the specific activities or components that have been utilized to accomplish the neuromuscular changes believed necessary to reduce noncontact ACL injury risk have varied dramatically. The activities for some of these programs have included stretching and flexibility exercises (Gilchrist, et al., 2008; Hewett, Lindenfield, Riccobene, & Noyes, 1999; Mandelbaum, et al., 2005), plyometric jumping exercises (Gilchrist, et al., 2008; Hewett, Lindenfield, Riccobene, & Noyes, 1999; Mandelbaum, et al., 2005; Myer G. , Ford, Brent, & Hewett, 2006), proper technique evaluation and feedback (Hewett, Lindenfield, Riccobene, & Noyes, 1999; Myklebust, et al., 2003; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005; Petersen, et al., 2005), education concerning “high risk” maneuvers (Gilchrist, et al., 2008; Petersen, et al., 2005), and balance training using balance boards and mats, wobble boards, or Swiss Ball exercises (Gilchrist, et al., 2008; Myer G. , Ford, Brent, & Hewett, 2006; Myklebust, et al., 2003; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005; Zebis, et al., 2008). While the activities vary in many of the neuromuscular training programs, the variation also extends into other components, such as duration, intensity, and frequency of training programs (Grindstaff, Hammill, Tuzson, & Hertel, 2006). The duration of individual training sessions can vary from 10 minutes per session (Petersen, et al., 2005) to 90 minutes (Gilchrist, et al., 2008; Hewett, Lindenfield, Riccobene, & Noyes, 1999), performed one (1) to five (5) times per week (Grindstaff, Hammill, Tuzson, & Hertel, 2006), and continue anywhere from six (6) weeks (Hewett, Lindenfield, Riccobene, & Noyes, 1999) to 18 weeks or more (Zebis, et al., 2008). Implementation of these programs has also varied from occurring prior to an athletic season as a component of pre-season conditioning (Hewett, Lindenfield, Riccobene, & Noyes, 1999) to occurring during an athletic season as part of a warm-up routine (Gilchrist, et al., 2008; Myklebust, et al., 2003; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005; Petersen, et al.,

2005). Grindstaff, et al. (2006) attempted to compare five (5) different neuromuscular training programs, and made some limited overall recommendations (10 to 20 minutes, three (3) days per week preseason and one (1) day per week during the season), but there is currently very little agreement or consensus among researchers concerning the duration, intensity, and frequency of neuromuscular training programs designed to reduce noncontact ACL injuries (DiStefano, Padua, DiStefano, & Marshall, 2009; Gilchrist, et al., 2008; Grindstaff, Hammill, Tuzson, & Hertel, 2006; Zebis, et al., 2008).

Even with all of the differences between the numerous intervention training programs, the results of these programs have generally been positive, with the risk of suffering an ACL injury according to one meta-analysis (Grindstaff, Hammill, Tuzson, & Hertel, 2006) decreasing on average by 70% compared to control groups. While the use of neuromuscular training programs as a method to help reduce the incidences of noncontact ACL injuries for possibly all athletes is encouraging, there still exists significant room for improvement, especially with a pooled numbers needed to treat (NNT) of 89 individuals (Grindstaff, Hammill, Tuzson, & Hertel, 2006). Additional research is needed to properly determine both effective and efficient protocols, with specific exercises and activities, as well as opportune time frames for implementation. While these results are positive, there are still a number of questions that exist concerning the most effective intervention program components and intervention strategies.

One of the concerns with these training programs is that they have been designed using lower extremity mechanics data collected in a similar manner to Hewett, et al. (2005), utilizing a novel task such as a drop landing. A basic assumption by researchers has been that drop landing performances simulate landing from an athletic performance move, such as a basketball rebound or volleyball block. There are some concerns with using a drop landing task, such as the

determination of what height to drop from, if there is any attempt to normalize the activity based upon participant characteristic or performance, and if the activity is one that accurately resembles an athletic activity of interest, specifically landing.

Height settings for drop landing studies focused on noncontact ACL injuries have ranged from 13.5cm (Ford, et al., 2006) to 100cm (Dufek & Bates, 1990), with very little, if any, justification provided for the selected height (Coffey, 2010). This rather large variance can limit the ability of researchers to compare the results and performance of participants across studies. It can be argued that different height settings of the drop equates to a change in the activity or task being performed by the participants. This possible change in “activity or task being performed” threatens to decrease the generalizability of the data and findings to similarly designed studies that used different height settings. There also does not currently exist a specific standardized height for drop landing research and limited justification, if any, exists for the use of specified heights (Coffey, 2010).

When examining the drop landing research studies, it is very rare to observe any information concerning the normalization of the drop height to account for discrepancies in individual characteristics or performance. This factor may be an especially important one for drop landing research studies that are attempting to identify differences in landing performances, and whether or not those differences may provide insight into noncontact ACL injury susceptibility. As discussed earlier, one study (Walsh, 2007) found differences in the maximum vertical jump performance between males and females. For the average female and male participant in a drop landing study, using a height setting of 30cm - a typical height setting (Coffey, 2010) - that activity is contextually very different. For females, the 30cm drop task is from a height that is 132% of the average maximum vertical jump, and for males the same task is

at a height that is only 79% of the average male maximum vertical jump. This difference in percentage of average maximum vertical jump (53%) suggests that contextually, a drop landing from the same height is different for the average female participant as compared to the average male participant, and may vary within each group as well. If the “activity” is then different for each gender or individual, the validity of studies comparing the landing mechanics of men and women or individuals from the same height and supposed task is questionable.

A suggestion that corrects this situation and thereby may produce more reliable and valid data concerning landing mechanics is studying participant landings from a task oriented jump. The use of a performed jump has been previously completed with ankle instability and the time to stabilization variable (Ross, Guskiewicz, & Yu, 2005). Ross, et al. (2005) used a maximal effort vertical jump as a baseline mark, and then used a Vertec Jump Trainer to set a jump height requirement of between 50% and 55% of the maximal vertical jump height. This jumping activity provided a task that is more representative of what is experienced during normal athletic activity, and an activity that the participants will be more familiar with rather than a novel drop landing. By having participants perform a task similar to what they would face during normal athletic activity, which is when noncontact ACL injuries occur, the results of the participants’ landing mechanics may provide greater insight than landing from a predetermined standardized height.

Additional information about lower extremity mechanics associated with ACL injuries may then lead to more effective intervention programs. This information could also be utilized in the future to design a clinical assessment tool that could be utilized to identify high risk athletes, both male and female. The ideal assessment would be completed in a matter of minutes and at a very minimal cost, and thus could be used much easier as a screening tool to help

identify those individuals who may be susceptible to non-contact ACL injuries. By identifying high risk individuals, athletic trainers and coaches can target particular individuals instead of an entire team, erasing the need to manage the compliance of an entire team with a preseason or in-season routine. The identified high risk athletes could then utilize specifically targeted neuromuscular training programs, additionally reducing concerns regarding compliance and providing a more effective intervention to reduce the incidence of noncontact ACL injuries.

Conclusions

While examining the research, it is clear that the mechanism and treatment of ACL injuries is not well defined (injury incidence, exact repair and rehabilitation protocols, predisposing or related factors, and precise intervention protocols). The injury is costly to repair (Huston, Greenfield, & Wojtys, 2000), and appears to be related to long term health concerns for the affected knee joint (Clatworthy & Amendola, 1999; Lebel, et al., 2008; Lohmander, Ostberg, Englund, & Roos, 2004; Roos, Adalberth, Dahlberg, & Lohmander, 1995; Shelbourne & Gray, 2009; Von Porat, Roos, & Roos, 2004). Preventive neuromuscular training interventions have shown the most promise by possibly reducing the risk of ACL injury by 70% (Grindstaff, Hammill, Tuzson, & Hertel, 2006), but additional research should be completed to help improve this result. It is possible that a more precise and targeted intervention could lead to better results with fewer injured athletes. The use of kinetic and kinematic information from athletic performances that resemble the activities in which the injuries occur could lead to additional information about the incidences of noncontact ACL injuries, the creation of a

screening tool to identify high risk individuals, and the creation of an effective targeted neuromuscular training program.

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Chapter 3: Do individuals display different lower extremity landing mechanics when performing different jump/landing tasks? Do these landing mechanics also differ between clinically assessed asymmetric and symmetric individuals?

Abstract

Anterior cruciate ligament (ACL) injuries are severe and damaging injuries that not only have immediate impacts on an individual's ability to play sports, but also have long-term impacts on activities of daily living. A number of studies have utilized a drop landing task in attempts to gain a greater understanding of how individuals land and how those landing performances are associated with ACL injuries. While drop landings have been a popular tool, there are very few recognized standards for drop landing tasks, and concerns have been raised that landing mechanics demonstrated during such a task may not accurately reflect the landing mechanics observed during landing from a functional task. Limb asymmetry has also been connected to incidents of ACL injuries, but it is unclear if clinically-assessed symmetry classifications from the functional ability test (FAT) correlate to differences in landing mechanics as observed using 3D motion analysis. The purpose of this study was to compare lower extremity landing mechanics of high school aged athletes using 3D motion analysis during three different landing tasks, and to assess possible group differences between clinically-assessed asymmetric and symmetric individuals. Twenty (20) male (mean age of 15.6 ± 1.2 years, mean height of 177.3 ± 8.9 cm, mean mass of 69.6 ± 10.4 kg, and mean vertical jump height of 22.0 ± 3.7 inches) and seventeen (17) female (mean age of 15.8 ± 1.0 years, mean height of 167.6 ± 4.6 cm, mean mass

of 61.1 ± 6.4 kg, and mean vertical jump height of 16.1 ± 2.6 inches) high school aged athletes were assessed for clinical asymmetry using the FAT, and had their landing performances examined with a 3D motion analysis system. All numbers expressed as \pm values above and throughout the document are calculated standard deviations. Participants completed three different tasks: drop landing (DL), adjusted height drop landing (AHDL), and vertical jump landing (VJL). A 2 X 3 repeated measures ANOVA (Landing Type X Symmetry Classification), grouped by gender with linear contrast analyses for Landtype and Symmetry were run for each of the examined kinetic and kinematic variables. Male and female participants did not demonstrate any differences in measured kinetics (ground reaction force and loading rate) between the three tasks. Male participants demonstrated a difference in maximum knee flexion during landing between the AHDL task (63.8 ± 13.6 degrees) as compared to the DL (53.5 ± 10.2 degrees) ($p=.0088$) and VJL (55.2 ± 12.2 degrees) ($p=.0269$) tasks. Both males and females displayed less hip adduction at impact (HADi) and in maximum (HADm) value in the two drop landing tasks (AHDL and DL) as compared to the VJL task. There were no differences demonstrated in landing mechanics for either gender based upon the grouping completed by the clinical symmetry assessment. Differences in hip joint mechanics during landing were observed between landing types (drop landing and functional task) for both genders. Future research should examine how these differences in hip joint mechanics impact the loading on the knee joint. While the groups as assigned by the FAT did not display differences in landing mechanics, future examination of clinical assessments is vital to identify a clinical tool that can detect individuals at risk for an ACL injury.

Introduction

The passage of Title IX in 1972, led to female participation in high school athletics increasing 9-fold in less than thirty years. During that same thirty year timeframe, male participation in high school athletics only increased by 3 percent (National Federation of State High School Associations, 2002). As the number of athletes has risen quickly over the years, unfortunately the number of injuries has also risen dramatically, especially for female athletes. A majority of the injuries affecting both male and female athletes are associated with the lower extremities, specifically the ankle and the knee (Bahr & Bahr, 1997; Barker & Beynnon, 1997; Colliander, Eriksson, & Herkel, 1986; Emery, Meeuwisse, & McAllister, 2006; Garrick, 1977).

While the noncontact anterior cruciate ligament (ACL) rupture rate for female athletes is significantly greater than their male counterparts (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994; Shea, Pfeiffer, Wang, Curtin, & Apel, 2004), the rupture of the ACL is one of the most common knee ligament injuries suffered by both male and female athletes (Beynnon, Johnson, Abate, Fleming, & Nichols, 2005; Ford, et al., 2006). A noncontact ACL rupture is a severe and damaging injury, and recently, the incidence rate among male and female athletes increased by almost 50 percent in a 10 year timeframe (Donnelly, Elliott, Ackland, & Doyle, 2012) and has increased even when compared to the rate of other sport-related injuries (Sampson, et al., 2011). This incidence rate for noncontact ACL injuries has been shown to range from 2 to 8 times greater risk for female athletes as compared to male athletes in the same sport (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994). It is estimated that between

175,000 and 200,000 ACL injuries occur in just the United States every year (Myer, Ford, & Hewett, 2004; Prodromos, Han, Rogowski, Joyce, & Shi, 2007), and based on the trend of increased incidence rates (Donnelly, Elliott, Ackland, & Doyle, 2012; Sampson, et al., 2011), that number can only be expected to keep increasing. An overwhelming majority of all ACL ruptures, nearly 70 percent, can be labeled as “noncontact,” meaning there was no external contact to the knee or body that directly caused the injury (Boden, Dean, Feagin, & Garrett, 2000). These noncontact ACL injuries are related to movement and movement patterns of the injured athlete, not impact forces from collisions with another athlete or object.

Over the past 20 years, a great deal of research has been done to try to identify the factors that are involved in the large gender discrepancy in the incidence rate of noncontact ACL ruptures, but a precise illustration of the multifactorial injury has yet to be created (Arendt, Bershadsky, & Agel, 2002; Shultz, et al., 2010). In March 2010, at a research retreat on the observed gender bias in noncontact ACL incidence rate, a number of consensus statements were updated from previous retreats concerning what is known about factors related to noncontact ACL ruptures, as well as areas of suggested future research. Researchers have divided noncontact ACL injury factors into the three following categories: (1) anatomical and structural, (2) hormonal, and (3) neuromuscular and biomechanical (Arendt, Bershadsky, & Agel, 2002; Shultz, et al., 2010). Due to the ability of clinicians and researchers to modify the neuromuscular and biomechanical factors, those factors have recently gained increased attention in attempting to examine the possible mechanical etiology of noncontact ACL injuries, as well as identifying “at risk” athletes (Chappell, Yu, Kirkendall, & Garrett, 2002; Hakkinen, Kraemer, & Newton, 1997; Hewett, et al., 2005; Huston, 2007; Huston & Wojtys, 1996; James, et al., 2001; Kanehisa, Okuyama, Ikegawa, & Fukunaga, 1996; Lephart, Abt, & Ferris, 2002).

A popular task that has been used by researchers to help assess and examine the neuromuscular factors possibly associated with noncontact ACL injury risk is a drop landing task. Hewett et. al. (2005) investigated a number of neuromuscular factors associated with a drop landing task with the goal of being able to better predict noncontact ACL injuries in female high school athletes. Their study examined the neuromuscular control of 205 adolescent female athletes during a drop landing task from a height of 31cm prior to a season, and then followed the participants to record noncontact ACL injuries during a particular season. The injured group displayed greater knee abduction angle at landing, knee abduction moment, and ground reaction force, as well as decreased stance time during landing. These results led the researchers to conclude that female athletes with increased dynamic valgus at impact and high knee abduction moments were at a greater risk to sustain a noncontact ACL injury. It is presently unclear if the same neuromuscular factors can be attributed to or utilized in examining the factors associated with the incidence of noncontact ACL injuries in male athletes.

A basic assumption by researchers utilizing drop landings is that these landing performances accurately represent landing from an athletic performance move such as a basketball rebound or volleyball block. Drop landing, however, may be a novel task, since the activity is one typically only used in either a research study setting (Edwards, Steele, & McGhee, 2010) or a workout routine (Bobbert, 1990), and not one typically performed during normal participation in a court or field sport. One recent study examined differences in lower extremity landing mechanics between a drop landing and a volleyball spike jump landing in skilled male volleyball players (Edwards, Steele, & McGhee, 2010). While the ability to generalize the results of this study is greatly reduced by the use of a very-sport specific task - sand volleyball spike jump - it does provide valuable insights into the use of drop landings. The results of this

study illustrated that in the drop landing condition, the participants landed with greater stiffness, as exemplified by less knee flexion at impact and greater ground reaction forces and loading rates when compared to the spike jump condition. While the vertical displacement differences might confound the results from this study, the results still suggest that when examining landing mechanics, laboratory activities such as drop landings, may not be accurately representative of an in-game activity, such as landing from a jump task (Edwards, Steele, & McGhee, 2010).

Another basic assumption of research utilizing a drop landing task is that individual differences in performance variables, such as maximum vertical jump height, are not taken into account when determining the specific height of the drop landing task (Coffey, 2010). Maximum vertical jumps, however, do vary by individual, and it is problematic to assume that performing a 30cm drop is the same activity for individuals with significantly different maximum vertical jump heights. However, despite the problematic nature of not taking into account this performance difference during drop landing research, most studies have focused on standardizing the height rather than the activity or task (Coffey, 2010).

A common in-game activity, such as a vertical jump landing (VJL) task, may be able to account for individual differences in performance and does not have the concern of being a novel task like a drop landing. Landing from a vertical jump has been associated with the occurrence of noncontact ACL injuries (Besier, Lloyd, Cochrane, & Ackland, 2001; Boden, Dean, Feagin, & Garrett, 2000; Marshall, Padua, & McGrath, 2007), and is better able to reproduce neuromuscular performances that more accurately represent those that occur during normal athletic participation in a variety of sports. A VJL task should provide more accurate information on landing mechanics that may lead to a better understanding of the factors

associated with noncontact ACL injuries and assist researchers in their attempt to reduce the incidence rate of these injuries.

It has also been suggested that lower extremity asymmetry may be a possible factor associated with incidents of noncontact ACL injuries (Pappas & Carpes, 2012). While these asymmetries have been found in both males and females, Pappas and Carpes (2012) found that the frequency of lower extremity asymmetry in frontal plane kinematics was much higher in females than males. This led them to conclude that this increased frequency may be an important factor in understanding the incidences of noncontact ACL injuries in female athletes. Clinical symmetry tests such as the functional ability test (FAT) have also been utilized in the past to assess neuromuscular control, specifically asymmetry in grouping a control group of normal individuals and ACL deficient individuals (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998). It is unclear if an asymmetrical/symmetrical grouping from a clinical symmetry test like the FAT could be a factor involved in an individual's demonstrated landing mechanics. If a clinical symmetry test could correlate to landing mechanics associated with noncontact ACL injuries, it would also be a more feasible option for screening athletes than a time- and financial-intensive screening utilizing 3D motion analysis.

The purpose of this study was to compare lower extremity landing mechanics of high school aged athletes using 3D motion analysis during three different landing tasks, and to assess possible group difference between clinically-assessed asymmetric and symmetric individuals.

Methods

Participants

Thirty seven (37) athletes participating in court and/or field sports (volleyball, field hockey, lacrosse, soccer, and basketball) were recruited from local high schools, as well as local organized athletic leagues. The twenty (20) male participants (10 Symmetric and 10 Asymmetric), had a mean age of 15.6 ± 1.2 years, a mean height of 177.3 ± 8.9 cm, a mean mass of 69.6 ± 10.4 kg, and a mean vertical jump height of 22.0 ± 3.7 inches. The seventeen (17) female participants (8 Symmetric and 9 Asymmetric), had a mean age of 15.8 ± 1.0 years, a mean height of 167.6 ± 4.6 cm, a mean mass of 61.1 ± 6.4 kg, and a mean vertical jump height of 16.1 ± 2.6 inches. The Symmetric and Asymmetric groups for both genders were not significantly different from each other based on age, height, mass, and vertical jump height, and the means for each group are shown in Table 1. A breakdown of the number of participants by sport of participation for each gender is shown in Table 2. The inclusion criterion that was utilized consisted of currently active athletes in court or field sports between the ages of 14 and 18 years of age. The exclusion criterion that was utilized consisted of previous lower extremity surgical repair, current injury or pain affecting the lower extremity, and lower extremity injury or pain that altered participation within one month prior to testing. Previous surgery or current and/or recent injury or pain could alter the movement patterns of a subject from their normal activity, and thus negatively impact the validity of the data. Participants and/or their parent/guardians were given instructions, inclusion and exclusion requirements for the study, and

the informed consent form to sign and complete. Virginia Commonwealth University Institutional Review Board reviewed this study and approved the use of human subjects.

Procedures

Participants completed a short warm up protocol, consisting of pedaling on a cycle ergometer at a self-selected light intensity for five minutes. Immediately following the warm up, participants completed four clinical hop tests to assess their functional performance if this had not been previously completed. The functional ability test (FAT) is comprised of four functional tests: a timed figure 8 (F8), a timed side hop (SH), up and down hop task (UD), and a single hop distance (HD). Based on the findings of Itoh, et al. (1998) the FAT was used as a clinical symmetry test. All four tests were completed as single leg hopping tasks twice, once with dominant limb and once with non-dominant limb, with a one-minute rest between tasks. The order in which the tasks were performed and limb order was counterbalanced. Participants were timed for the F8, SH, and UD tasks using a handheld stop watch. For the HD task, the distance of the performed hop was manually measured and recorded for each limb. Performances for dominant and non-dominant limbs were then compared for all four tasks, and based upon the results from previous findings (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998), individuals were classified as asymmetric if limb differences for any of the four tasks were determined to be equal to or greater than 0.81s (F8), 0.72s (UD), 0.78s (SH), and 0.2m (HD). Individuals were permitted to practice each task for a maximum of two minutes before the timed or measured trial

was completed. If a participant needed to restart a task due to either participant or collection error, they were given a one-minute rest period prior to restarting the task.

After completing the FAT, participants were fitted with Oxide® aqua shoes to standardize the contact surface between the foot and the landing surface. The use of aqua shoes has been demonstrated previously to be a way to standardize footwear, and has not been shown to be risk factor for injury in biomechanical studies examining landing mechanics (Coffey, James, Sizer, & Williams, 2002; James, et al., 2001). Participants then performed three maximum one-step vertical jump attempts using the Vertec Jump Trainer (Sports Imports, Columbus, OH), which has been shown to be valid and reliable for measuring vertical jump performance (Leard, et al., 2007). The greatest height of the three jumps was designated as the individual participant's maximum vertical jump height. Anthropometric data (height, weight, and limb lengths) were also collected and recorded for all participants.

After completion of maximum vertical jump height testing, participants were prepped for completing the three landing tasks in a predetermined and counterbalanced order. The Vicon Motion Capture System™ (Vicon, Centennial, CO, USA,) utilizes sixteen near infrared tracking sensors placed bilaterally at the following locations: toe, heel, ankle, shank, knee, thigh, anterior superior iliac spine, and posterior superior iliac spine, as specified by the Vicon Plug in Gait model (Russell, Palmieri, Zinder, & Ingersoll, 2006). A graphic detailing the placement of these markers can be seen in Figure 1. These sensors were used in a manner that has been shown to be valid and reliable to define the lower extremity segments and motions of the knee in three dimensions during the landings via the Vicon Plug in Gait model (Davis, Ounpuu, Tyburski, & Gage, 1991; Russell, Palmieri, Zinder, & Ingersoll, 2006).

Participants performed five (5) bilateral landings for each of the three experimental conditions (DL, AHDL, and VJL) onto the imbedded Bertec Force Plate, Type 4060-nonconducting (Bertec Corporation, Columbus, OH, USA) sampling at 1000 Hz. A 12-camera Vicon Motion Capture System™ (100 Hz) near infrared tracking system (Vicon, Centennial, CO, USA) was utilized to track the 3D sensors and to synchronize kinetic and kinematic data. Landing in the DL condition was accomplished by having subjects step-off the jumping platform (right foot first) and land with both feet on the force platform. To simulate a game-like situation, during the landing participants were asked to catch a basketball thrown to them from a research assistant standing directly in front of them. Participants were instructed to focus on catching the basketball rather than cognitively focusing on the landing. Unsuccessful landings that included loss of balance, extreme asymmetry, dropping the basketball, or other procedural error were discarded and repeated. Landings in the AHDL condition were the same as the DL condition, except the height of the drop was set at a height equal to 80% of the participant's maximum vertical jump height, as utilized in a prior study (Coffey, James, Sizer, & Williams, 2002; James, et al., 2001). Landing in the VJL condition was accomplished by having the participant complete a task-oriented one-step vertical jump performance and landing with both feet on the designated force platform. Participants were asked to perform a vertical jump while reaching for a target set on the Vertec (Sports Imports, Columbus, OH) at 80% of the individual's maximum vertical jump height. Trials in which the participant was not able to reach the target or did not land with both feet on the force platform were discarded and repeated. In total, 15 trials, five (5) for each task, were collected, processed, and utilized for data analysis.

Data Processing

Vicon MXControl™ software (Vicon, Centennial, CO, USA), which internally synchronized collected kinetic and the kinematic was used to process raw recorded data through the Dynamic Plug in Gait Vicon Nexus pipeline. Kinetic and kinematic data was filtered utilizing a Woltring cross-validity quintic spline routine (MSE = 20) as described previously in the literature (Woltring, 1986) and more recently validated (Molloy, Salazar-Torres, Kerr, McDowell, & Cosgrove, 2008). Filtered data was then exported from Vicon MXControl™ to Visual3D Professional v4.00.19 (C-Motion Inc., Germantown, Maryland) for post-processing analysis of individual kinetic and kinematic variables.

The kinetic variables examined were vertical ground reaction force (GRF) and loading rate (LR) of the GRF from impact to peak GRF. Impact was defined as the point in time when the vertical ground reaction force was at least 10N (Ford, Myer, & Hewett, 2007). The kinematic variables of interest were maximum knee flexion angle (KFm), knee flexion angle at impact (KFi), maximum knee abduction angle (KAm), knee abduction angle at impact (KAi), maximum internal knee rotation angle (KIRm), internal knee rotation angle at impact (KIRi), maximum hip adduction angle (HADm), and hip adduction angle at impact (HADi). The timeframe in which the maximum value was determined for the kinematic variables of interest was designated as the moment of impact to 200ms, which would encompass the timeframe in which ACL injuries have been shown to occur (Cassidy, Hangalur, Sabharwal, & Chandrashekar, 2013). Mean values for all ten variables were calculated for each participant in each of the three landing conditions by averaging across the five trials that were performed in each landing condition.

Data Analysis

All statistical analysis for this study was performed using SAS version 9.4 software (SAS Corp., Cary, NC). Grouped by gender, a 2 X 3 repeated measures ANOVA (Landing Type X Symmetry Classification) with linear contrast analyses by Landtype and Symmetry were run for each of the ten measures. ANOVA assumptions were checked for all significant models and statistical significance was established as $\alpha = 0.05$.

Results

Kinetics

The results from the ANOVA models demonstrated that for both genders there were no significant differences between the three landing conditions for either GRF or LR. There were also no observed significant differences for either observed kinetic variables between the Symmetric and Asymmetric groups for both the male and female participant groups. Table 3 provides the calculated means and standard deviations for the recorded kinetic variables, GRF and LR.

Kinematics

The results from the ANOVA models demonstrated that for the male participants, there were significant differences in the observed HADm ($p=.005$), HADi ($p=.001$), and KFm ($p=.02$) across the different landing conditions. The linear contrast analysis showed that the male participants demonstrated a shift towards greater hip adduction in the VJL task at impact (HADi: -2.7 ± 4.1 degrees) and during landing (HADm: -0.2 ± 4.1 degrees) compared to the observed performance in the DL (HADi: -7.4 ± 4.2 degrees, $p=.0011$; HADm: -4.7 ± 4.6 degrees, $p=.0029$) and AHDL (HADi -7.3 ± 4.6 degrees, $p=.0014$; HADm: -4.4 ± 4.9 degrees, $p=.0060$) landing conditions. Males also displayed greater KFm during landing in the AHDL condition (63.8 ± 13.6 degrees) as compared to the DL (53.5 ± 10.2 degrees) ($p=.0088$) and VJL (55.2 ± 12.2 degrees) ($p=.0269$). None of the other observed kinematic variables (KFi, KAm, Kai, KIRm, or KIRi) were significantly different between landing conditions or symmetry classification. No interaction effects were observed for any of the observed kinematic variables amongst the male participants. Table 4 contains the observed means and standard deviations for the measured kinematic variables for the male participants.

For female participants, the results from the ANOVA models showed that significant differences existed for HADm ($p=.01$) and HADi ($p=.0004$) between landing conditions. The linear contrast analyses also showed that the Female participants demonstrated a shift towards greater hip adduction for the VJL task (HADm: 1.4 ± 3.6 degrees; HADi; -1.7 ± 3.6 degrees) as compared to the DL (HADm: -2.8 ± 4.7 degrees, $p=.0077$; HADi: -7.2 ± 4.4 degrees, $p=.0003$) and AHDL (HADm: -2.2 ± 4.7 degrees, $p=.0218$; HADi: -6.8 ± 3.9 degrees, $p=.0007$). None of the other observed kinematic variables (KFm, KFi, KAm, Kai, KIRm, or KIRi) were significantly

different between landing conditions or symmetry classification. No interaction effects were observed for any of the observed kinematic variables amongst the female participants. Table 5 contains the observed means and standard deviations for the measured kinematic variables for the female participants.

Discussion

Drop landings have become a popular tool for researchers to examine lower extremity landing mechanics and understand how those mechanics can be used to predict noncontact ACL injuries. Some of these studies have produced fairly accurate predictor models based on 3D motion analysis findings for identifying athletes at risk for noncontact ACL injuries (Hewett, et al., 2005). There are, however, some concerns with using a task such as a set height drop landing as the primary task in the creation of such a predictor model. One methodological concern has been that there is no universally recognized standard for the height of a drop landing task (Coffey, 2010). Others have also suggested that while a drop landing can be a very controlled lab activity, it may not accurately represent a landing during a sporting competition (Edwards, Steele, & McGhee, 2010). The purpose of this study was to compare lower extremity landing mechanics of high school aged athletes using 3D motion analysis during three different

landing tasks and to assess possible group difference between clinically assessed asymmetric and symmetric individuals.

Kinetics

The results from a previous study comparing drop landing to a functional jump landing (Edwards, Steele, & McGhee, 2010) suggested that we would observe greater overall landing stiffness with increases in GRF and LR in the two drop landing conditions (DL and AHDL) as compared to the functional jump landing condition (VJL). The results of this current study did not show this same difference, with GRF and LR not being statistically different in any of the three conditions for either males or females. While Edwards, et al. (2009) attempted to control for the height of the activity, it was acknowledged that there may have been height differences between the drop landing and the functional jump that influenced the outcome. For the female participants in this study, however, the heights for all three landing activities were close in value (DL=11.8in; AHDL and VJL=12.8±2.1in). This suggests that on average, the female participants would have experienced virtually similar potential energy levels due to landing height across the three tasks. The resulting similar GRF and LR values suggest that the type of activity (drop landing versus functional jumping task) does not impact the GRF or the timing of the loading during landing. For the male participants, however, the heights for the landing activities were not very similar (DL=11.8in; AHDL and VJL=17.6±3.0), suggesting that there would be differences in potential energy levels, resulting in demonstrated differences in the GRF and LR variable. While the average GRF and LR were higher in the AHDL and VJL

conditions as compared to the DL as expected, these differences were not statistically significant. These results for the male participants suggest that even when differences in height and potential energy exist, there is not a difference in the demonstrated GRF or LR between a drop landing and a functional jumping task.

Kinematics

While it was expected that the DL and AHDL tasks would result in more stiff landings, specifically decreased knee flexion (Edwards, Steele, & McGhee, 2010), this was not the case for either males or females. The male subjects actually demonstrated an increase in KFM in the AHDL condition as compared to the other two tasks. While the novelty of the drop landing did not produce differences in KFM for the DL and VJL conditions, the additional height between the AHDL and DL resulted in the male participants demonstrating additional knee flexion during landing. This increase in KFM is likely an adaptation in movement pattern to assist with energy absorption due to the increase in potential energy from the DL to AHDL conditions. The demonstration of increased KFM in the AHDL condition as compared to the VJL suggests that when the height of the activity is kept the same, male individuals land in a stiffer fashion from a functional jumping task than from a drop landing task. This difference in KFM that was observed in the male participants did not exist for the female participants. As discussed earlier, with the lack of differences in GRF and LR, the lack of a sizeable difference in the height of the three tasks for female participants meant that they did not have to adapt their landing pattern due to changes in potential energy.

While a majority of the kinematic variables examined as part of this study did not demonstrate any differences between the three tasks for either males or females, this was not true for hip adduction. Both HADm and HADi were significantly different in the VJL condition as compared to the two drop landing conditions for both males and females. While the height of the task did not appear to influence the degree of hip adduction, the type of activity did, with both male and female participants demonstrating greater adduction values in the functional jumping task (VJL) as compared to the drop landing (AHDL and DL). It is unclear why almost all of the knee joint kinematics displayed no differences between the tasks, while there were differences in hip movement both at impact and over the course of the landing.

Due to lab design limitations, joint moments could not be calculated for this study, but one would expect that changes in the hip joint kinematics would alter the joint moments of the hip and possibly the knee as it could shift the location of the center of mass. It has been demonstrated that movement of the hip in the frontal plane towards greater adduction does result in increased knee valgus and knee abduction moment in runners (Williams & Isom, 2012). Knee abduction moment has been shown to be a predictor of ACL injuries (Hewett, et al., 2005), and if greater knee abduction moment is demonstrated during a functional jumping task as compared to a drop landing task, it may provide more detailed information about individual knee abduction moments, and thus prove to be a better predictive task.

The findings concerning differences in hip joint kinematics across the task types also supports previous recommendations that while the injury and significant research have centered around the knee joint, additional information from the proximal and distal joints (hip and ankle), may provide valuable insight into understanding noncontact ACL injuries (Wild, Steele, & Munro, 2012). This study, like large number of landing studies, only focused on the lower

extremities. Building off the recommendations of Wild, et al. (2012), future studies should not only examine the landing mechanics associated with the hip, but also examine the movement patterns of the trunk. A number of training programs designed to reduce ACL injuries have shown that plyometric exercises and balance training are important components (Stevenson, Beattie, Schwartz, & Busconi, 2014); the trunk and upper extremities play a role in how individuals land and should be taken into consideration when examining landing mechanics.

Symmetry

The use of the FAT previously to identify ACL deficient individuals (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998) led to the hypothesis that the FAT might also be able to predict differences in lower extremity mechanics during a landing. The FAT is easy to set up and implement, and is also comparatively inexpensive. If the classification of symmetric/asymmetric could correlate to different landing mechanics, it could be a useful tool for preventing injuries. Surprisingly, the symmetric and asymmetric groups for both males and females, as determined by the FAT, did not display lower extremity landing mechanics that differed between the groups. While Itoh, et al. (1998) did not provide specifics about the athletic level of their participants they did provide average age (ACL deficient group=23.1 years; ACL intact group=21.6 years), which was significantly older than the participants enrolled in this study (male=15.5 years; female=15.9 years). It is possible that decreases in neuromuscular control of the younger age group, resulted in hopping task performances differences that had a higher likelihood that these participant would be classified as asymmetric. The FAT also uses

specified values for maximum observed performance differences between limbs to designate symmetric/asymmetric classification. This clearly works for an older population, but for this age group, there existed some wide variations in the amount of time that it took to complete some of the components of the FAT. Future studies should examine if the use of a percentage difference between limbs rather than a specified time or distance, may provide greater specificity in classification of symmetry/asymmetry.

Limitations

Limitations of this study include the use of 3D motion analysis. 3D motion analysis is a widely utilized tool to examine how individuals move and provides valuable insight into movement patterns, injury prevention, and much more. It is, however, far from perfect (McGinley, Baker, Wolfe, & Morris, 2009), as it has its own limitations in regards to accuracy, and those limitations should be taken into consideration when examining 3D motion analysis results.

Another limitation of this study was the young age of the participants. This age group was selected due to 14-18 year old athlete being at the highest risk for ACL injuries, with injury risk peaking at 16 years of age (Shea, Pfeiffer, Wang, Curtin, & Apel, 2004). Examining this group provides valuable insights into the landing mechanics demonstrated by this group. Reduced neuromuscular control is believed to be a primary influencing factor into why this group experiences a greater risk of injury (Hewett, Myer, & Ford, 2004). Past studies have also shown that neuromuscular control strategies can change due to maturation (Oliver & Smith,

2010). The impacts of reduced neuromuscular control and possible alterations in neuromuscular strategies could lead to increases in movement variation, which would increase the level of difficulty in attempting to identify potential differences in landing mechanics between tasks and groups. Overall this results in limiting the generalizability of the results to high school athletes between the ages of 14 and 18 years of age.

One other limitation of this study is that participants' past participation in any kind of neuromuscular training program was not obtained upon enrollment and could not be taken into consideration in the data analysis. These training programs, which are various, are not very widespread and have not been incorporated into workouts or practices for most teams or schools. It was brought to light after the study started that at least one of the schools and teams where participants were recruited from, utilized training protocols or interventions designed to reduce the risk of ACL injuries. It is unclear which participants were involved in these training programs or what their compliance was, but it is possible that their performance may have been influenced by them.

Future

Future studies attempting to gain a greater understanding of lower extremity mechanics during landing should use a full-body 3D analysis model rather than just a lower extremity model to take into account trunk position changes as a result of the observed changes in hip mechanics. Another component that needs further investigation concerns the possible implications rising from comparing landing mechanics in a drop landing task to those of a

functional task, and how results may be impacted by the age or maturity and possible skill level of participants. A previous study utilizing the Landing Error Scoring System (LESS) to assess high-risk movement patterns found that skill level did not impact the number errors observed (Theiss, et al., 2014). Theiss, et al. (2014) utilized college age participants, and it has been shown previously that high school age athletes demonstrate more errors as measured by the LESS as compared to college age individuals (Smith, et al., 2012). It is unclear how these factors may intertwine with each other in regards to impact landing mechanics. Future studies should also examine the use of a modified FAT or other clinical assessment as a tool to help detect changes in landing mechanics than can currently only be assessed utilizing 3D motion analysis.

Conclusion

The use of a functional jumping task impacted the hip joint mechanics, specifically adduction, as compared to the mechanics demonstrated during a drop landing. While the knee joint mechanics did not differ outside of KFM for male participants between the tasks, alterations to demonstrated hip landing mechanics would alter the application of forces through the knee joint. This suggests that while the use of a drop landing task is very popular for lower extremity injury prevention research, it does not as accurately represent an individual's landing mechanics at the hip as a functional jumping task. The use of a functional injury screening tool is vital to

providing direct and targeted neuromuscular training interventions. The FAT may be a promising tool for adults to clinically assess asymmetry. With adolescents, however, its symmetric/asymmetric groupings do not demonstrate different landing mechanics during any of the three different landing conditions utilized in this study. Further refinement of the FAT to use a percentage difference between limb performances, rather than a predetermined specific value, may be more appropriate with this adolescent population.

Table 1. Table of demographic means for participants both overall and in subgroups based on clinical assessment of symmetry.

Group	Height (cm)	Mass (kg)	Age (years)	Vertical Jump (inches)
Males	177.3 ± 8.9	69.6 ± 10.4	15.6 ± 1.2	22.0 ± 3.7
Male Asymmetric	177.1 ± 9.5	68.7 ± 9.2	15.8 ± 1.6	21.5 ± 4.9
Male Symmetric	177.5 ± 8.8	70.5 ± 11.9	15.4 ± 0.7	22.5 ± 2.3
Females	167.6 ± 4.6	61.1 ± 6.4	15.9 ± 1.0	16.0 ± 2.6
Female Asymmetric	166.4 ± 4.7	61.9 ± 7.6	16.0 ± 1.0	14.6 ± 2.2
Female Symmetric	169.3 ± 4.4	60.3 ± 5.2	15.8 ± 1.0	17.6 ± 1.9

Table 2. Table of participants by sport of participation for both male and female participants.

Sport of Participation	Males	Females
Basketball	3	2
Volleyball	3	4
Field Hockey	0	3
Soccer	9	1
Lacrosse	5	7

Table 3. Table of means and standard deviations of kinetic variables for participants both overall and in subgroups based on clinical assessment of symmetry.

Group	Vertical Ground Reaction Force (times body weight)			Loading Rate (times body weight/sec)		
	AHDL	DL	VJL	AHDL	DL	VJL
Males	6.4 ± 2.3	5.3 ± 1.3	6.9 ± 1.9	131.2 ± 68.5	93.7 ± 36.4	142.5 ± 73.7
Male Asymmetric	6.2 ± 1.8	5.0 ± 1.0	7.2 ± 2.2	116.9 ± 51.6	85.2 ± 36.4	145.5 ± 84.1
Male Symmetric	6.6 ± 2.8	5.5 ± 1.6	6.6 ± 1.6	145.5 ± 82.4	102.1 ± 36.3	139.4 ± 66.2
Females	4.0 ± 1.3	4.0 ± 1.4	4.2 ± 0.9	52.5 ± 17.1	59.3 ± 24.8	60.5 ± 20.5
Female Asymmetric	3.8 ± 0.7	3.8 ± 0.7	4.2 ± 0.9	56.4 ± 20.4	63.2 ± 29.8	61.4 ± 17.9
Female Symmetric	4.3 ± 1.7	4.2 ± 2.0	4.3 ± 1.0	47.6 ± 11.0	42.9 ± 9.0	59.3 ± 24.9

Table 4. Table of means and standard deviations of kinematic variables for male participants both overall and in subgroups based on clinical assessment of symmetry. All variables below are shown in degrees. (^A=significantly different from DL and VJL; ^B=significantly different from AHDL and DL)

Kinematic Variables	Males Overall			Male Symmetric			Male Asymmetric		
	AHDL	DL	VJL	AHDL	DL	VJL	AHDL	DL	VJL
KFm	63.8 ± 13.6 ^A	53.5 ± 10.2	55.2 ± 12.2	68.7 ± 13.4	55.7 ± 10.1	57.3 ± 14.0	58.9 ± 12.5	51.4 ± 10.3	53.1 ± 10.5
KFi	15.2 ± 6.3	12.0 ± 5.8	12.5 ± 5.8	17.5 ± 4.2	13.2 ± 5.8	14.2 ± 4.7	12.9 ± 7.4	10.7 ± 5.8	10.7 ± 6.4
KAm	19.9 ± 8.6	17.7 ± 7.5	20.2 ± 9.2	18.2 ± 8.2	16.1 ± 6.5	19.3 ± 11.1	21.5 ± 9.1	19.3 ± 8.5	21.2 ± 7.4
KAi	7.9 ± 5.1	7.2 ± 4.4	6.7 ± 5.8	8.1 ± 5.1	7.0 ± 4.1	7.1 ± 6.5	7.8 ± 5.5	7.5 ± 4.8	6.3 ± 5.4
HAm	-4.4 ± 4.9	-4.7 ± 4.6	-0.2 ± 4.1 ^B	-5.0 ± 5.1	-5.7 ± 5.2	-1.0 ± 4.0	-3.7 ± 5.0	-3.7 ± 4.0	0.6 ± 4.2
HAi	-7.3 ± 4.6	-7.4 ± 4.2	-2.7 ± 4.1 ^B	-8.2 ± 5.0	-8.6 ± 4.7	-2.3 ± 4.2	-6.3 ± 4.1	-6.2 ± 3.6	-3.1 ± 4.0
KIRm	8.4 ± 10.7	7.2 ± 10.7	6.3 ± 9.5	10.3 ± 13.1	9.2 ± 12.8	7.1 ± 11.1	6.5 ± 7.9	5.1 ± 8.4	5.6 ± 8.1
KIRi	-4.0 ± 7.7	-6.1 ± 8.1	-5.5 ± 7.9	-2.0 ± 9.4	-4.0 ± 9.8	-3.9 ± 10.2	-5.9 ± 5.4	-8.2 ± 5.8	-7.1 ± 4.6

Table 5. Table of means and standard deviations of kinematic variables for female participants both overall and in subgroups based on clinical assessment of symmetry. All variables below are shown in degrees. (^=significantly different from AHDL and DL)

Kinematic Variables	Females Overall			Female Symmetric			Female Asymmetric		
	AHDL	DL	VJL	AHDL	DL	VJL	AHDL	DL	VJL
KFm	71.8 ± 13.5	69.5 ± 13.3	68.3 ± 11.4	71.9 ± 13.8	69.1 ± 15.7	69.4 ± 10.8	71.8 ± 14.1	69.9 ± 11.9	67.4 ± 12.4
KFi	20.7 ± 5.7	20.5 ± 6.3	19.2 ± 4.1	20.6 ± 6.1	20.1 ± 6.8	19.1 ± 4.5	20.7 ± 5.7	20.9 ± 6.2	19.3 ± 4.1
KAm	5.3 ± 8.0	5.1 ± 7.5	6.6 ± 9.5	6.6 ± 9.6	7.3 ± 8.6	9.6 ± 11.4	4.1 ± 6.7	3.1 ± 6.3	4.0 ± 7.2
KAi	2.3 ± 5.6	1.9 ± 4.8	2.0 ± 6.1	2.3 ± 6.7	2.6 ± 5.0	3.3 ± 7.1	2.3 ± 4.8	1.3 ± 4.8	0.8 ± 5.2
HAm	-2.2 ± 4.7	-2.8 ± 4.7	1.4 ± 3.6 ^A	-3.4 ± 3.5	-3.6 ± 4.7	-0.1 ± 3.7	-1.1 ± 5.5	-2.2 ± 4.9	2.7 ± 3.2
HAi	-6.8 ± 3.9	-7.2 ± 4.4	-1.7 ± 3.6 ^A	-7.6 ± 4.3	-7.4 ± 4.6	-2.3 ± 2.5	-6.0 ± 3.6	-7.0 ± 4.5	-1.3 ± 4.4
KIRm	8.6 ± 8.8	8.7 ± 8.3	8.3 ± 8.2	11.3 ± 10.9	10.5 ± 10.5	9.7 ± 10.7	6.1 ± 6.0	7.0 ± 5.9	7.1 ± 5.6
KIRi	-4.5 ± 7.2	-4.3 ± 6.5	-4.9 ± 6.9	-1.8 ± 9.5	-2.3 ± 8.5	-2.6 ± 8.2	-6.9 ± 3.4	-6.1 ± 3.7	-6.7 ± 5.1

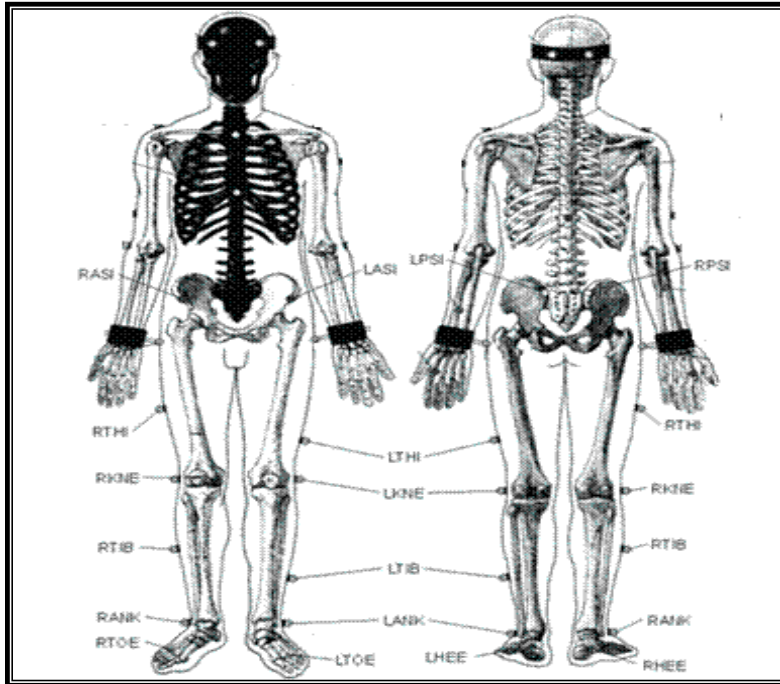


Figure 1. Visual representation of reflective marker placement for lower extremity Plug in Gait model. The graphic is adapted from the original included in the Vicon Motion Capture system™ manual.

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Chapter 4: Do clinically assessed asymmetric individuals display a greater relative risk for lower extremity ligamentous injury as compared to clinically assessed symmetric individuals? Does the type of landing task affect the ability of lower extremity landing mechanics to predict occurrences of lower extremity ligamentous injury? Are any of these task-based predictions stronger than a prediction based on symmetry/asymmetry?

Abstract

Anterior cruciate ligament (ACL) injuries as well as other lower extremity ligamentous injuries can be severe and damaging and not only have immediate impacts on an individual's ability to play sports, but also have long-term impacts on activities of daily living. A number of neuromuscular training programs have been created to successfully help reduce an athlete's risk of suffering injury. While these interventions have been generally successful, there is a need to identify those athletes at high risk of injury in order to provide better targeted interventions to prevent injury. Limb asymmetry has been connected to incidents of ACL injuries, but it is unclear if clinically-assessed symmetry classifications from the functional ability test (FAT) may be accurately able to predict lower extremity ligamentous injuries in an adolescent population. 3D motion analysis utilizing drop landings has been previously used to create a predictor model for ACL injury. There are very few recognized standards for drop landing tasks, and concerns have been raised that landing mechanics demonstrated during such a task that have been used to create an injury predictor model may not accurately reflect the landing mechanics observed during landing from a functional task. The purpose of this study was to determine if clinically-

assessed asymmetric individuals displayed a greater relative risk for lower extremity ligamentous injury as compared to clinically-assessed symmetric individuals. This study also sought to compare the injury prediction ability of this clinical symmetry assessment with that of three prediction models based off lower extremity landing mechanics during three different landing conditions.

Ninety-six (96) male (mean age 16.0 ± 1.3 years) and sixty-nine (69) female (mean age 15.8 ± 1.2) high school-aged athletes participating in court and/or field sports (volleyball, field hockey, lacrosse, soccer, and basketball) were assessed for clinical asymmetry using the FAT. Seventy (70) males (mean age 16.0 ± 1.3) and fifty-six (56) females (mean age 15.9 ± 1.2) completed a follow-up injury surveillance questionnaire. Based upon the reported injuries and clinical symmetry assessment, relative risk of injury was calculated for each gender. A logistic regression was also completed to examine the prediction ability of the FAT. A subgroup of twenty (20) male (mean age of 15.6 ± 1.2 years, mean height of 177.3 ± 8.9 cm, mean mass of 69.6 ± 10.4 kg, and mean vertical jump height of 22.0 ± 3.7 inches) and seventeen (17) female (mean age of 15.8 ± 1.0 years, mean height of 167.6 ± 4.6 cm, mean mass of 61.1 ± 6.4 kg, and mean vertical jump height of 16.1 ± 2.6 inches) participants also had their landing performances examined with a 3D motion analysis system. All numbers expressed as \pm values above and throughout the document are calculated standard deviations. Participants completed three different tasks: drop landing (DL), adjusted height drop landing (AHDL), and vertical jump landing (VJL), and stepwise logistic regression was completed for each gender to identify kinetic and kinematic variables possibly associated with incidences of lower extremity ligamentous injuries. The clinical symmetry assessment from the FAT did not produce statistically significant relative risk of injuries or injury prediction models based upon asymmetry for either

males or females. The injury prediction models for each of the three landing tasks failed to select any statistically significant kinetic or kinematic variables to include for either gender.

Future research should examine the use of a modified FAT or other clinical screening tool as a way to identify athletes at risk of suffering a lower extremity ligamentous injury in order to provide a more targeted injury prevention protocol. While the three landing tasks were not able to generate a significant predictor model of injury, future examination of drop landings and tasks that take into account individual performance in the creation of injury prediction models is still needed.

Introduction

As the number of athletes participating in high school level athletics has risen quickly over the years, the number of sports injuries has also risen dramatically, especially for female athletes (Donnelly, Elliott, Ackland, & Doyle, 2012; Sampson, et al., 2011). A majority of the injuries affecting both male and female athletes are associated with the lower extremities, specifically the ankle and the knee (Bahr & Bahr, 1997; Barker & Beynon, 1997; Colliander, Eriksson, & Herkel, 1986; Emery, Meeuwisse, & McAllister, 2006; Garrick, 1977). It is estimated that between 175,000 and 200,000 anterior cruciate ligament (ACL) injuries occur in just the United States every year (Myer, Ford, & Hewett, 2004; Prodromos, Han, Rogowski, Joyce, & Shi, 2007), and based on the trend of increased incidence rates (Donnelly, Elliott, Ackland, & Doyle, 2012; Sampson, et al., 2011), that number can only be expected to keep

increasing. The financial costs attributed to these injuries can be quite steep, including treatment, possible surgery, rehabilitation, and long-term care for possible secondary injuries. As an example, the average cost of surgical management and post-operative rehabilitation for an athlete with an ACL injury has been estimated to be approximately \$17,000 (Huston, Greenfield, & Wojtys, 2000). For high school and collegiate female athletes in the United States alone, the medical expenditures for just ACL injuries have been estimated to be approximately \$646 million annually (Huston, Greenfield, & Wojtys, 2000). Another study extrapolating from other cost studies and world population estimates suggested that approximately \$1 billion is spent annually in the United States on ACL injury management (Donnelly, Lloyd, Elliott, & Reinbolt, 2012). These estimates do not include any of the costs associated with the management or treatment of secondary knee joint injuries such as knee osteoarthritis (OA), a degenerative joint disorder which has also been associated with ACL injury incidences (Lebel, et al., 2008; Lohmander, Ostenberg, Englund, & Roos, 2004; Shelbourne & Gray, 2009).

Due to the impacts of these athletic injuries -- trauma, lost participation time, financial costs, and secondary injury incidence -- significant energy has been focused on ways to prevent injuries, especially ACL injuries from occurring in the first place. The development and implementation of neuromuscular training programs as an intervention technique to reduce ACL injury risk has been a point of more emphasis even as the specific etiology of these injuries is still debated (Silvers, Giza, & Mandelbaum, 2005). The specific components of these training programs have changed over time, and collectively lack standardization concerning the activities utilized, length and duration of intervention, and frequency of intervention activity (Coffey, 2010; Grindstaff, Hammill, Tuzson, & Hertel, 2006). Even without these standardizations, these neuromuscular training programs have been shown to greatly reduce the risk of suffering an

ACL injury by an average of 70% as compared to control groups (range: 48% to 100%) (Grindstaff, Hammill, Tuzson, & Hertel, 2006).

While the use of neuromuscular training programs as a method to help reduce the incidences of noncontact ACL injuries is encouraging, there still exists significant room for improvement, especially with a pooled numbers needed to treat (NNT) of 89 individuals (Grindstaff, Hammill, Tuzson, & Hertel, 2006). One of these concerns is that it is currently unclear what the most effective components, interventions strategies, and techniques for these training programs should be (Grindstaff, Hammill, Tuzson, & Hertel, 2006; Myer, Ford, & Hewett, 2006). There also does not exist specific criteria as to which athletes should be participating in these types of neuromuscular training interventions, and thus many of these interventions are given as group warm-up or exercises (Gilchrist, et al., 2008; Myklebust, et al., 2003; Olsen, Myklebust, Engebretsen, Holme, & Bahr, 2005; Petersen, et al., 2005), rather than individualized prevention. If athletic trainers could identify which of their athletes were at a higher risk for injury, these interventions could be more directly targeted, which would result in increased injury prevention.

Another concern with these prevention programs is that a large number of them have a number presumptions incorporated into their designs concerning lower extremity mechanics data collected utilizing a novel task such as a drop landing. An examination by Hewett et al. (2005) has been one of the most influential of these studies that investigated a number of neuromuscular factors associated with a drop landing task with the goal of being able to better predict noncontact ACL injuries in female high school athletes. Their study examined the neuromuscular control of 205 adolescent female athletes during a drop landing task from a height of 31cm prior to a season, and then followed the participants to record noncontact ACL injuries

during a particular season. The injured group displayed greater knee abduction angle at landing, greater knee abduction moment, and greater ground reaction force, as well as decreased stance time during landing. These results led the researchers to conclude that female athletes with increased dynamic valgus at impact and high knee abduction moments were at a greater risk to sustain a noncontact ACL injury. It is presently unclear if the same neuromuscular factors can be attributed to or utilized in examining the factors associated with the incidence of noncontact ACL injuries in male athletes.

One basic assumption by researchers utilizing drop landings is that these landing performances accurately represent landing from an athletic performance move such as a basketball rebound or volleyball block. Drop landing, however, may be a novel task, since the activity is one typically only used in either a research study setting (Edwards, Steele, & McGhee, 2010) or a workout routine (Bobbert, 1990), and not one typically performed during normal participation in a court or field sport. One recent study examined differences in lower extremity landing mechanics between a drop landing and a volleyball spike jump landing in skilled male volleyball players (Edwards, Steele, & McGhee, 2010). While the ability to generalize the results of this study is greatly reduced by the use of a very sport specific task - sand volleyball spike jump - it does provide valuable insights into the use of drop landings. The results of this study illustrated that in the drop landing condition, the participants landed with greater stiffness, as exemplified by less knee flexion at impact and greater ground reaction forces and loading rates when compared to the spike jump condition. While the vertical displacement differences might confound the results from this study, the results still suggest that when examining landing mechanics, laboratory activities such as drop landings may not be accurately representative of an in-game activity such as landing from a jump task (Edwards, Steele, & McGhee, 2010).

Another basic assumption of research utilizing a drop landing task is that individual differences in performance variables such as maximum vertical jump height are not taken into account when determining the specific height of the drop landing task (Coffey, 2010). Maximum vertical jumps do vary by individual, and it is problematic to assume that performing a 30cm drop is the same activity for individuals with significantly different maximum vertical jump heights. However, despite the problematic nature of not taking into account this performance difference during drop landing research, most studies have focused on standardizing the height rather than the activity or task (Coffey, 2010).

A common in-game activity such as a vertical jump landing (VJL) task may be able to account for individual differences in performance and would not be considered a novel task like a drop landing. Landing from a vertical jump has been associated with the occurrence of noncontact ACL injuries (Besier, Lloyd, Cochrane, & Ackland, 2001; Boden, Dean, Feagin, & Garrett, 2000; Marshall, Padua, & McGrath, 2007), and is better able to reproduce neuromuscular performances that more accurately represent those that occur during normal athletic participation in a variety of sports. A VJL task should provide more accurate information on landing mechanics that may lead to a better predictor model for injuries such as ACL injuries, and should assist researchers in their attempt to reduce the incidence rate of these injuries.

It has also been suggested that lower extremity asymmetry may be a factor associated with incidents of noncontact ACL injuries (Pappas & Carpes, 2012). While these asymmetries have been found in both males and females, Pappas and Carpes found that the frequency of lower extremity asymmetry in frontal plane kinematics was much higher in females than in males. This led them to conclude that this increased frequency may be an important factor in

understanding the incidences of noncontact ACL injuries in female athletes. Clinical symmetry tests such as the functional ability test (FAT) have also been utilized in the past to assess neuromuscular control, specifically asymmetry in grouping a control group of normal individuals and ACL deficient individuals (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998). It is unclear if an asymmetrical/symmetrical grouping from a clinical symmetry test like the FAT could provide insight into injury instances. If a clinical symmetry test could accurately predict risk of injury, it would be a more effective option for screening athletes as compared to a time- and financial-intensive screening utilizing 3D motion analysis. Identifying these high-risk athletes would allow athletic training staff to provide better targeted interventions and thus reduce the incidence rate of injuries such as ACL tears.

The purpose of this study was to determine if clinically-assessed asymmetric individuals displayed a greater relative risk for lower extremity ligamentous injury as compared to clinically-assessed symmetric individuals. This study also sought to compare the injury prediction ability of this clinical symmetry assessment with that of three prediction models based off lower extremity landing mechanics during three different landing conditions.

Methods

Participants

One hundred-and-sixty-five (165) athletes participating in court and/or field sports (volleyball, field hockey, lacrosse, soccer, and basketball) were recruited from local high schools, and from local organized athletic leagues. Ninety-six (96) males (mean age 16.0 ± 1.3 years) and sixty-nine (69) females (mean age 15.8 ± 1.2) completed the FAT, with thirty-nine (39) males and thirty-two (32) females clinically assessed as asymmetric. Seventy (70) males (mean age 16.0 ± 1.3) and fifty-six (56) females (mean age 15.9 ± 1.2) completed the injury surveillance questionnaire, with a response rate of 72.9% and 81.2% respectively. A breakdown of these groups, asymmetric assessment, and response rates are shown below in Table 1. The number of participants recruited and completed injury surveys by sport of participation for each gender are shown in Table 2.

Thirty-seven (37) athletes were recruited from the initial group into the subgroup to complete a 3D analysis of landing mechanics. The twenty (20) male participants (10 symmetric and 10 asymmetric), had a mean age of 15.6 ± 1.2 years, a mean height of 177.3 ± 8.9 cm, a mean mass of 69.6 ± 10.4 kg, and a mean vertical jump height of 22.0 ± 3.7 inches. The seventeen (17) female participants (8 symmetric and 9 asymmetric), had a mean age of 15.8 ± 1.0 years, a mean height of 167.6 ± 4.6 cm, a mean mass of 61.1 ± 6.4 kg, and a mean vertical jump height of 16.1 ± 2.6 inches. The symmetric and asymmetric groups for both genders were not significantly different from each other based on age, height, mass, and vertical jump height, and the means for each group are shown in Table 3. A breakdown of the number of participants in the subgroup

that completed the 3D motion analysis by sport of participation for each gender is shown in Table 4.

The inclusion criterion that was utilized consisted of currently active athletes in court or field sports between the ages of 14 and 18 years of age. The exclusion criterion that was utilized consisted of previous lower extremity surgical repair, current injury or pain affecting the lower extremity, and lower extremity injury or pain that altered participation within one month prior to testing. Previous surgery or current and/or recent injury or pain could alter the movement patterns of a subject from their normal activity, and thus negatively impact the validity of the data. Participants and/or their parent/guardians were given instructions, inclusion and exclusion requirements for the study, and the informed consent form to sign and complete. Virginia Commonwealth University Institutional Review Board reviewed this study and approved the use of human subjects.

Procedures

Participants completed four clinical hop tests to assess their functional performance; the functional ability test (FAT) is comprised of four functional tests: a timed figure 8 (F8), a timed side hop (SH), up and down hop task (UD), and a single hop distance (HD). Based on the findings of Itoh, et al. (1998), the FAT was used as a clinical symmetry test. All four tests were completed as single-leg hopping tasks twice, once with dominant limb and once with non-dominant limb, with a one-minute rest between tasks. Both the order in which the tasks were performed and limb order were counterbalanced. Participants were timed for the F8, SH, and

UD tasks using a handheld stopwatch. For the HD task, the distance of the performed hop was manually measured and recorded for each limb. Performances for dominant and non-dominant limbs were then compared for all four tasks, and based upon the results from previous findings (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998), individuals were classified as asymmetric if limb differences for any of the four tasks were determined to be equal to or greater than 0.81s (F8), 0.72s (UD), 0.78s (SH), and 0.2m (HD). Individuals were permitted to practice each task for a maximum of two minutes before the timed or measured trial was completed. If a participant needed to restart a task due to either participant or collection error, they were given a one-minute rest period prior to restarting the task.

The 3D motion analysis subgroup participants started their follow-up session by completing a short warm up protocol, consisting of pedaling on a cycle ergometer at a self-selected light intensity for five minutes if it had not been completed prior. Participants were fitted with Oxide® aqua shoes to standardize the contact surface between the foot and the landing surface. The use of aqua shoes has been previously demonstrated to be a way to standardize footwear, and has not been shown to be a risk factor for injury in biomechanical studies examining landing mechanics (Coffey, James, Sizer, & Williams, 2002; James, et al., 2001). After the warm-up and footwear fitting, participants then performed three maximum one-step vertical jump attempts using the Vertec Jump Trainer (Sports Imports, Columbus, OH), which has been shown to be valid and reliable for measuring vertical jump performance (Leard, et al., 2007). The greatest height of the three jumps was designated as the individual participant's maximum vertical jump height. Anthropometric data (height, weight, and limb lengths) were also collected and recorded for all participants.

After completion of maximum vertical jump height testing, participants were prepped for completing the three landing tasks in a predetermined and counterbalanced order. The Vicon Motion Capture System™ (Vicon, Centennial, CO, USA,) utilizes sixteen near infrared tracking sensors placed bilaterally at the following locations: toe, heel, ankle, shank, knee, thigh, anterior superior iliac spine, and posterior superior iliac spine, as specified by the Vicon Plug-in Gait model (Russell, Palmieri, Zinder, & Ingersoll, 2006). A graphic detailing the placement of these markers can be seen in Figure 1. These sensors were used in a manner that has been shown to be valid and reliable to define the lower extremity segments and motions of the knee in three dimensions during the landings via the Vicon Plug-in Gait model (Davis, Ounpuu, Tyburski, & Gage, 1991; Russell, Palmieri, Zinder, & Ingersoll, 2006).

Participants performed five (5) bilateral landings for each of the three experimental conditions (DL, AHDL, and VJL) onto the imbedded Bertec Force Plate, Type 4060-nonconducting (Bertec Corporation, Columbus, OH, USA) sampling at 1000 Hz. A 12-camera Vicon Motion Capture System™ (100 Hz) near infrared tracking system (Vicon, Centennial, CO, USA) was utilized to track the 3D sensors and to synchronize kinetic and kinematic data. Landing in the DL condition was accomplished by having subjects step off the jumping platform (right foot first) and land with both feet on the force platform. To simulate a game-like situation, participants were asked to catch a basketball thrown to them from a research assistant standing directly in front of them during the landing. Participants were instructed to focus on catching the basketball rather than cognitively focusing on the landing. Unsuccessful landings that included loss of balance, extreme asymmetry, dropping the basketball, or other procedural error were discarded and repeated. Landings in the AHDL condition were the same as the DL condition, except the height of the drop was set at a height equal to 80% of the participant's maximum

vertical jump height, as utilized in a prior study (Coffey, James, Sizer, & Williams, 2002; James, et al., 2001). Landing in the VJL condition was accomplished by having the participant complete a task-oriented one-step vertical jump performance and landing with both feet on the designated force platform. Participants were asked to perform a vertical jump while reaching for a target set on the Vertec (Sports Imports, Columbus, OH) at 80% of the individual's maximum vertical jump height. Trials in which the participant was not able to reach the target or did not land with both feet on the force platform were discarded and repeated. In total, fifteen (15) trials, five (5) for each task, were collected, processed, and utilized for data analysis.

Injury Surveillance

When completing the initial clinical assessment, participants provided an email address for researchers to utilize for follow-up on injury status. Participants were sent an email to this address with a link to complete an injury questionnaire through REDCap (Research Electronic Data Capture), a web-based secure data collection tool. The survey asked participants to identify any lower extremity injuries they had suffered since their initial test, and if they were injured to provide information on the injury, including: name of the injury, how the injury occurred, and who diagnosed or confirmed the injury. Links to the survey were sent to participants at both the halfway point and end of the season. Non-responding participants were sent at least two follow-up reminders to encourage completion of the survey. The injury responses were reviewed and included if the injury was indeed a lower extremity ligamentous injury, was non-contact in nature, and had been diagnosed or confirmed by an ATC or physician.

Kinematic Data Processing

Vicon MXControl™ software (Vicon, Centennial, CO, USA), which internally synchronized collected kinetic and kinematic data was used to process raw recorded data through the Dynamic Plug-in Gait Vicon Nexus pipeline. Kinetic and kinematic data was filtered utilizing a Woltring cross-validity quintic spline routine (MSE = 20) as described previously in the literature (Woltring, 1986) and more recently validated (Molloy, Salazar-Torres, Kerr, McDowell, & Cosgrove, 2008). Filtered data was then exported from Vicon MXControl™ to Visual3D Professional v4.00.19 (C-Motion Inc., Germantown, Maryland) for post-processing analysis of individual kinetic and kinematic variables.

The kinetic variables examined were vertical ground reaction force (GRF) and loading rate (LR) of the GRF from impact to peak GRF. Impact was defined as the point in time when the vertical ground reaction force was at least 10N (Ford, Myer, & Hewett, 2007). The kinematic variables of interest were maximum knee flexion angle (KFm), knee flexion angle at impact (KFi), maximum knee abduction angle (KAm), knee abduction angle at impact (KAi), maximum internal knee rotation angle (KIRm), internal knee rotation angle at impact (KIRi), maximum hip adduction angle (HADm), and hip adduction angle at impact (HADi). The timeframe in which the maximum value was determined for the kinematic variables of interest was designated as the moment of impact to 200ms, which would encompass the timeframe in which ACL injuries have been shown to occur (Cassidy, Hangalur, Sabharwal, & Chandrashekar, 2013). Mean values for all ten (10) variables were calculated for each participant in each of the three landing conditions by averaging across the five trials that were performed in each landing condition.

Data Analysis

All statistical analysis for this study was performed using SAS version 9.4 software (SAS Corp., Cary, NC). Based upon the results from the clinical assessment of symmetry and the provided lower extremity ligamentous injury data, a relative risk table was created for symmetric and asymmetric athletes grouped by gender. A logistic regression was also completed utilizing the clinical assessment of symmetry and injury status to examine the use of the clinical assessment as a predictor tool. For the 3D motion analysis subgroup, a stepwise logistic regression was utilized for each of the three landing tasks (VJL, DL, and AHDL) using the recorded dependent variables from the 3D motion analysis and participant ACL injury status at the conclusion of one season, to create three lower extremity ligamentous injury predictors. For all comparisons, participants were grouped by gender and statistical significance was established as $\alpha = 0.05$.

Results

Clinical Symmetry Assessment

Of the seventy (70) male participants that responded with injury status information, only seven (7) lower extremity ligamentous injuries were reported. Ankle sprain or roll was the most commonly reported injury (5). One (1) Achilles injury and one (1) patella subluxation were also reported for the male participants. For the fifty-six (56) female participants that responded with their injury status, only four (4) injuries were reported, and all four (4) were ankle sprains or roll injuries. The injuries for both males and females were almost evenly divided between clinically-assessed symmetric (males: 4; females: 2) and asymmetric (males: 3; females: 2) groups. A breakdown of the injuries by clinical assessment is shown in Table 5. The relative risk of injury based upon clinical symmetry assessment and injury status was calculated for both males (1.35; $p = .678$) and females (1.15; $p = .882$), with neither one being statistically significant. The logistic regressions that were completed based upon the clinical assessment of symmetry and provided injury data resulted in non-significant models for both male ($\text{Chi}^2 = .169$; $p = .681$) and female ($\text{Chi}^2 = .022$; $p = .882$) participants.

3D Motion Analysis Injury Predictor Models

The thirty-seven (37) subgroup participants (20 male and 17 female) that completed the 3D motion analysis resulted in eighteen (18) males and sixteen (16) females that completed the injury surveillance survey. Four (4) injuries (3 male; 1 female) were reported by participants. Similar to the responses from the clinical assessment, ankle sprain or roll was the most common injury (3 injuries), followed by one (1) report of a patella subluxation. Injury data, including injury survey response numbers and injury numbers for this subgroup, is shown in Table 6.

The stepwise logistic regressions for all three landing types utilizing the ten (10) kinetic and kinematic variables all resulted in no variables meeting the required significance level for inclusion in any of the three models.

Discussion

Injury prevention training programs or interventions have been successful at reducing injuries (Grindstaff, Hammill, Tuzson, & Hertel, 2006), however the overall effectiveness of these programs could be increased if they were implemented in a more targeted manner. There is a need for better identification of athletes that demonstrate a higher risk of suffering an injury such as an ACL tear. Better identification of these high-risk athletes would provide an opportunity for a more targeted and specific intervention, which would increase the effectiveness of these neuromuscular training programs. The purpose of this study was to determine if

clinically-assessed asymmetric individuals displayed a greater relative risk for lower extremity ligamentous injury as compared to clinically-assessed symmetric individuals. This study also sought to compare the injury prediction ability of this clinical symmetry assessment with that of three prediction models based off lower extremity landing mechanics during three different landing conditions.

Clinical Symmetry Assessment

It had been theorized that athletes who were categorized as asymmetric using the FAT would display a greater relative risk of injury. In this study, however, the calculated relative risk of lower extremity ligamentous injury for both male and female athletes was not different between clinically-assessed symmetric and asymmetric athletes. It was also theorized that a clinical assessment of asymmetry completed prior to an athletic season would be an accurate predictor of injury incidence. This, however, was not this case, and the utilized clinical assessment tool did not provide symmetry classifications that allowed for the creation of an accurate predictor model for either male ($\text{Chi}^2 = .169$; $p = .681$) or female ($\text{Chi}^2 = .022$; $p = .882$) athletes. Asymmetry has been previously linked to injury occurrence (Pappas & Carpes, 2012), but for this study, the classification based on the FAT was not linked to the observed injuries. It is possible that the ability of the FAT in this study to predict injuries was limited by the small number of reported injuries. In this study, the reported injury rate for all lower extremity ligamentous injuries for female athletes was 7% and 10% for male athletes. By comparison,

Hewett et al. (2005) found a 4.4% seasonal injury rate for just ACL injuries in their study of high school basketball and soccer players.

The use of the FAT previously to identify ACL deficient individuals (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998) and the linkage of asymmetry to injury (Pappas & Carpes, 2012) led to the hypothesis that the FAT might also be able to predict lower extremity ligamentous injuries. The FAT is easy to set up and implement, and is also comparatively inexpensive when compared to a 3D motion analysis. If the classification of symmetric/asymmetric could predict injuries, it could be a useful tool to identify high-risk athletes, allowing for the implementation of targeted interventions to prevent injuries. Based on the findings from Itoh et al. (1998), it was surprising that the symmetric and asymmetric groups for both males and females, as determined by the FAT, did not display statistically different relative risks or predictor models of injury.

While Itoh, et al. (1998) did not provide specifics about the athletic level of their participants, they did provide average age (ACL deficient group=23.1 years; ACL intact group=21.6 years), which was significantly older than the participants that provided injury status information as a part of this study (male=16.0 years; female=15.9 years). It is possible that decreases in neuromuscular control of the younger age group resulted in hopping task performance differences that had a higher likelihood that these participants would be classified as asymmetric.

The FAT also uses specified values for maximum observed performance differences between limbs to designate symmetric/asymmetric classification. This clearly works for an older population, but for this age group, there existed some wide variations in the amount of time that it took to complete some of the components of the FAT. Future studies should examine if the

use of a percentage difference between limbs rather than a specified time or distance may provide greater specificity in classification of symmetry/asymmetry.

3D Motion Analysis Prediction

It was expected that each of the three landing conditions would be able to produce a predictor model with at least a few of the kinetic and kinematic variables collected utilizing 3D motion analysis. This was not the case, and none of the three tasks resulted in predictor models that selected even a single variable in a stepwise logistic regression. It was hypothesized that the model created from data collected during the VJL condition would provide the most accurate predictor, as it could be able to account for individual differences in performance and did not have the quality of being a novel task like the two drop landing tasks. However, since none of the three landing types resulted in the creation of a significant predictor model, this study was unable to compare the prediction abilities based on stepwise logistic regressions of the different tasks. It is highly likely that these models, similar to the clinical symmetry assessment, were hampered by a small number of reported lower extremity ligamentous injuries (male: 3; female: 1). The females in the 3D motion analysis subgroup only reported a seasonal injury rate of 6.25%, and males reported a higher injury rate of 16.7%. Both were lower than what would be expected for lower extremity ligamentous injuries.

It is possible that the prediction models based on the 3D motion analysis data was limited due to a lab design limitation that hindered the ability for joint moments to be calculated for this study. While attempts were made to compensate for this by including hip motion, as one

would expect that changes in the hip joint kinematics would alter the joint moments of the hip and possibly the knee as it could shift the location of the center of mass, knee moment data was not directly included in the modeling. It has been demonstrated that movement of the hip in the frontal plane towards greater adduction does result in increased knee valgus and knee abduction moment in runners (Williams & Isom, 2012). Knee abduction moment has been shown to be a predictor of ACL injuries (Hewett, et al., 2005), and if greater knee abduction moment is demonstrated during a functional jumping task as compared to a drop landing task, it may provide more detailed information about individual knee abduction moments, and thus prove to be a better predictive task.

Limitations

Limitations of this study include the use of 3D motion analysis. 3D motion analysis is a widely utilized tool to examine how individuals move and provides valuable insight into movement patterns, injury prevention, and much more. It is, however, far from perfect (McGinley, Baker, Wolfe, & Morris, 2009), as it has its own limitations in regards to accuracy, and those limitations should be taken into consideration when examining 3D motion analysis results.

Another limitation of this study was the young age of the participants. This age group was selected due to 14-18 year old athletes being at the highest risk for ACL injuries, with injury risk peaking at 16 years of age (Shea, Pfeiffer, Wang, Curtin, & Apel, 2004). Examining this group provides valuable insights into the landing mechanics they demonstrated. Reduced

neuromuscular control is believed to be a primary influencing factor into why this group experiences a greater risk of injury (Hewett, Myer, & Ford, Decreases in neuromuscular control about the knee with maturation in female athletes., 2004). Past studies have also shown that neuromuscular control strategies can change due to maturation (Oliver & Smith, 2010). The impacts of reduced neuromuscular control and possible alterations in neuromuscular strategies could lead to increases in movement variation, which would increase the level of difficulty in attempting to identify predictor models for injuries using individual performances in the FAT and 3D motion analysis.

One other limitation of this study is that participants' past participation in any kind of neuromuscular training program was not obtained upon enrollment and could not be taken into consideration in the data analysis. These training programs, which are various, are not very widespread and have not been incorporated into workouts or practices for most teams or schools. It was brought to light toward the end of the study that at least one of the schools and teams where participants were recruited from utilized training protocols or interventions designed to reduce the risk of ACL injuries. It is unclear which participants were involved in these training programs or what their compliance was, but it is possible that their performance may have been influenced by them. Possibly related to these interventions, the reported lower extremity ligamentous injury rate for the participants in this study was greatly reduced from what was expected. If a number of participants had participated in a neuromuscular training program, this could have resulted in a fewer number of injuries occurring.

Future

Future studies attempting to gain a greater understanding of lower extremity mechanics during landing and how they might predict injury should use a full-body 3D analysis model rather than just a lower extremity model to take into account trunk position changes. Another component that needs further investigation concerns the possible implications arising from comparing landing mechanics in a drop landing task to those of a functional task, and how those results may be impacted by the age or maturity and possible skill level of participants. A previous study utilizing the Landing Error Scoring System (LESS) to assess high-risk movement patterns found that skill level did not impact the number of errors observed (Theiss, et al., 2014). Theiss, et al. (2014) utilized college age participants, and it has been shown previously that high school age athletes demonstrate more errors as measured by the LESS as compared to college age individuals (Smith, et al., 2012). It is unclear how these factors may intertwine with each other in regards to impact landing mechanics, and thus prediction ability. Future studies should also examine the use of a modified FAT or other clinical assessment as a tool to help predict injury incidence. As noted previously, there are concerns with utilizing the FAT with this age group, which is at high risk for injury, but a modified FAT or other clinical screening tool may prove to be effective at identifying athletes at risk of a lower extremity ligamentous injury.

Conclusion

The use of a functional injury screening tool, such as the FAT, is needed to identify at-risk athletes and provide direct and targeted neuromuscular training interventions. The FAT may be a promising tool for adults to clinically assess asymmetry. With adolescents, however, its symmetric/asymmetric groupings do not demonstrate an ability to predict lower extremity ligamentous injury for either male or female athletes. Further refinement of the FAT to use a percentage difference between limb performances, rather than a predetermined specific value, may be more appropriate with this adolescent population, which may result in a more accurate injury predictor tool.

While the 3D motion analysis of the three landing conditions in this study did not result in a single accurate predictor model of injury, this may be more a reflection of small injury numbers than the tasks themselves. It was expected that a task that accounted for individual differences in performance would be more accurate as a predictor. While this was not the case here, this study also did not rule out the importance of accounting for individual performance when creating a predictor model. Further investigation is warranted to examine these implications as they relate to injuries and injury prevention.

Table 1. Table of clinical symmetry assessment and response rates for participants, both overall and in subgroups, based on clinical assessment of symmetry.

Group	Recruited	Injury Survey Completed	Response Rate
Males	96	70	72.9%
<i>Male Asymmetric</i>	39	25	64.1%
<i>Male Symmetric</i>	57	45	78.9%
Females	69	56	81.2%
<i>Female Asymmetric</i>	32	26	81.3%
<i>Female Symmetric</i>	37	30	81.1%

Table 2. Table of participants by sport of participation overall and for completing injury surveillance for both male and female participants.

Sport of Participation	Males	Males with Response	Females	Females with Response
Basketball	30	23	18	15
Volleyball	32	16	9	9
Field Hockey	0	0	7	5
Soccer	24	22	10	9
Lacrosse	10	9	25	18

Table 3. Table of demographic means for participants, both overall and in subgroups, based on clinical assessment of symmetry.

Group	Height (cm)	Mass (kg)	Age (years)	Vertical Jump (inches)
Males	177.3 ± 8.9	69.6 ± 10.4	15.6 ± 1.2	22.0 ± 3.7
<i>Male Asymmetric</i>	<i>177.1 ± 9.5</i>	<i>68.7 ± 9.2</i>	<i>15.8 ± 1.6</i>	<i>21.5 ± 4.9</i>
<i>Male Symmetric</i>	<i>177.5 ± 8.8</i>	<i>70.5 ± 11.9</i>	<i>15.4 ± 0.7</i>	<i>22.5 ± 2.3</i>
Females	167.6 ± 4.6	61.1 ± 6.4	15.9 ± 1.0	16.0 ± 2.6
<i>Female Asymmetric</i>	<i>166.4 ± 4.7</i>	<i>61.9 ± 7.6</i>	<i>16.0 ± 1.0</i>	<i>14.6 ± 2.2</i>
<i>Female Symmetric</i>	<i>169.3 ± 4.4</i>	<i>60.3 ± 5.2</i>	<i>15.8 ± 1.0</i>	<i>17.6 ± 1.9</i>

Table 4. Table of participants for subgroup completing 3D motion analysis by sport of participation for both male and female participants.

Sport of Participation	Males	Females
Basketball	3	2
Volleyball	3	4
Field Hockey	0	3
Soccer	9	1
Lacrosse	5	7

Table 5. Table of reported injuries broken down by clinical assessment of symmetry for both male and female participants.

Group	Symmetric	Asymmetric
Males with Response	45	25
Male Injuries	4	3
Females with Response	30	26
Female Injuries	2	2

Table 6. Table of injury survey responses and reported injuries broken down by gender for participants in 3D motion analysis subgroup.

Group	3D Tested	Injury Response	Number of Injuries	Injuries
Males	20	18	3	Ankle Sprain/Roll (2) Patellar Subluxation (1)
Females	17	16	1	Ankle Sprain/Roll (1)

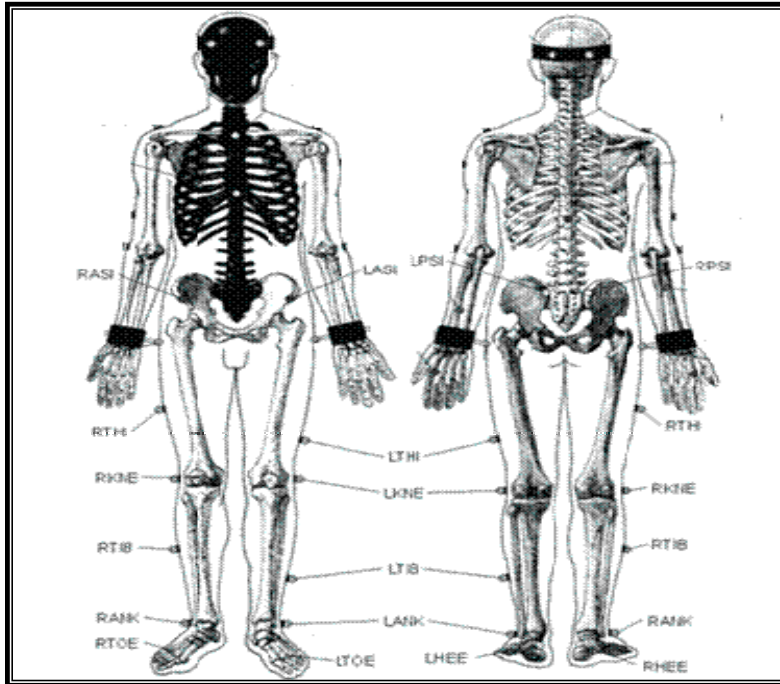


Figure 1. Visual representation of reflective marker placement for lower extremity Plug-in Gait model. The graphic is adapted from the original included in the Vicon Motion Capture System™ manual.

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Works Cited

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Chapter 5: Do individuals display different external knee abduction moments across three landing tasks and does this differ between clinically-assessed asymmetric and symmetric individuals?

Abstract

Anterior cruciate ligament (ACL) injuries are severe and damaging injuries that not only have immediate impacts on an individual's ability to play sports, but which also have long-term impacts on activities of daily living. A number of studies have utilized a drop landing task in attempts to gain a greater understanding of how individuals land and how those landing performances are associated with ACL injuries. While drop landings have been a popular tool, there are very few recognized standards for drop landing tasks, and concerns have been raised that landing mechanics demonstrated during such a task may not accurately reflect the landing mechanics observed during landing from a functional task. Limb asymmetry has also been connected to incidents of ACL injuries, but it is unclear if clinically-assessed symmetry classifications from the functional ability test (FAT) correlate to differences in landing mechanics as observed using 3D motion analysis. The purpose of this study was to utilize 3D motion analysis to compare the peak knee joint abduction moment (KAmom) during three different landing tasks, and to assess possible group differences between clinically-assessed asymmetric and symmetric individuals. Ten (10) recreationally active males were participants (5 symmetric and 5 asymmetric), and they had a mean age of 20.2 ± 3.6 years, a mean height of 175.3 ± 7.3 cm, a mean mass of 75.6 ± 11.4 kg, and a mean vertical jump height of 19.8 ± 5.1

inches. All numbers expressed as \pm values above and throughout the document are calculated standard deviations. Participants were assessed for clinical asymmetry using the FAT, and had their landing performances examined with a 3D motion analysis system. Participants completed three different tasks: drop landing (DL), adjusted height drop landing (AHDL), and vertical jump landing (VJL). A 2 X 3 repeated measures ANOVA (Landing Type X Symmetry Classification), grouped by right and left side with linear contrast analyses for Landtype and Symmetry were run for KAmom. Participants did not demonstrate any differences in measured KAmom between the three tasks for either the right or left side. A Levene's test for equal variance did show that for the right KAmom, there was significantly less variance in performance across participants in the AHDL condition than the DL and VJL conditions. There were no differences demonstrated in landing mechanics for either right or left KAmom based upon the grouping completed by the clinical symmetry assessment. Future research should examine the implications of this difference in variance in the AHDL condition as it relates to identifying performance outliers that may be more prone to ACL injury, and if the results are consistent in populations at a higher risk of suffering an ACL injury (females and high school athletes). While the groups as assigned by the FAT did not display differences in KAmom, future examination of clinical assessments is vital to identify a clinical tool that can detect individuals at risk for an ACL injury.

Introduction

Participation in high school athletics for both girls and boys has increased over the years since the passage of Title IX in 1972 (National Federation of State High School Associations, 2002). With this increase in participation rates, the number of injuries has also risen dramatically, especially for female athletes. A majority of the injuries affecting both male and female athletes are associated with the lower extremities, specifically the ankle and the knee (Bahr & Bahr, 1997; Barker & Beynnon, 1997; Colliander, Eriksson, & Herkel, 1986; Emery, Meeuwisse, & McAllister, 2006; Garrick, 1977). While the noncontact anterior cruciate ligament (ACL) rupture rate for female athletes is significantly greater than their male counterparts (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994; Shea, Pfeiffer, Wang, Curtin, & Apel, 2004), the rupture of the ACL is one of the most common knee ligament injuries suffered by both male and female athletes (Beynnon, Johnson, Abate, Fleming, & Nichols, 2005; Ford, et al., 2006).

A noncontact ACL rupture is a severe and damaging injury, and recently the incidence rate among male and female athletes increased by almost 50 percent in a 10 year timeframe (Donnelly, Elliott, Ackland, & Doyle, 2012). Noncontact ACL injuries have also shown an increase in frequency when compared to the rate of other sport-related injuries (Sampson, et al., 2011). The incidence rate for noncontact ACL injuries has been shown to be anywhere from 2 to 8 times greater for female athletes as compared to male athletes in the same sport (Arendt, Agel, & Dick, 1999; Harmon & Ireland, 2000; Nyland, Shapiro, Stine, Horn, & Ireland, 1994). It is estimated that between 175,000 and 200,000 ACL injuries occur in just the United States every

year (Myer, Ford, & Hewitt, 2004; Prodromos, Han, Rogowski, Joyce, & Shi, 2007), and based on the trend of increased incidence rates (Donnelly, Elliott, Ackland, & Doyle, 2012; Sampson, et al., 2011), that number can only be expected to keep growing. An overwhelming majority of all ACL ruptures -- nearly 70 percent -- can be labeled as noncontact, meaning there was no external contact to the knee or body that directly caused the injury (Boden, Dean, Feagin, & Garrett, 2000). These noncontact ACL injuries are related to movement and movement patterns of the injured athlete as opposed to impact forces from collisions with another athlete or object.

Over the past 20 years, a great deal of research has focused on trying to identify the factors that are involved in the large gender discrepancy in the incidence rate of noncontact ACL ruptures, but a precise illustration of the multifactorial injury has yet to be created (Arendt, Bershadsky, & Agel, 2002; Shultz, et al., 2010). A significant effort has been put forth in attempting to examine the possible mechanical etiology of noncontact ACL injuries, as well as identifying at risk athletes (Chappell, Yu, Kirkendall, & Garrett, 2002; Hakkinen, Kraemer, & Newton, 1997; Hewett, et al., 2005; Huston, 2007; Huston & Wojtys, 1996; James, et al., 2001; Kanehisa, Okuyama, Ikegawa, & Fukunaga, 1996; Lephart, Abt, & Ferris, 2002). By focusing on the biomechanical and neuromuscular factors associated with the injury, which may be modified, researchers are attempting to better understand those factors and tailor interventions to help prevent ACL injuries from occurring.

A popular task that has been used by researchers to help assess and examine the neuromuscular factors possibly associated with noncontact ACL injury risk is a drop landing task. Hewett et al. (2005) investigated a number of neuromuscular factors associated with a drop landing task with the goal of being able to better predict noncontact ACL injuries in female high school athletes. Their study examined the neuromuscular control of 205 adolescent female

athletes during a drop landing task from a height of 31cm prior to a season, and then followed the participants to record noncontact ACL injuries during a particular season. The injured group displayed greater knee abduction angle at landing, knee abduction moment, and ground reaction force, as well as decreased stance time during landing. These results led the researchers to conclude that female athletes with increased dynamic valgus at impact and high knee abduction moments were at a greater risk to sustain a noncontact ACL injury. It is presently unclear if the same neuromuscular factors can be attributed to or utilized in examining the factors associated with the incidence of noncontact ACL injuries in male athletes.

A basic assumption by researchers utilizing drop landings is that these landing performances accurately represent landing from an athletic performance move such as a basketball rebound or volleyball block. Drop landing, however, may be a novel task, since the activity is one typically only used in either a research study setting (Edwards, Steele, & McGhee, 2010) or a workout routine (Bobbert, 1990), and not one typically performed during normal participation in a court or field sport. One recent study examined differences in lower extremity landing mechanics between a drop landing and a volleyball spike jump landing in skilled male volleyball players (Edwards, Steele, & McGhee, 2010). While the ability to generalize the results of this study is greatly reduced by the use of a very sport-specific task - sand volleyball spike jump - it does provide valuable insights into the use of drop landings in understanding lower extremity landing mechanics. The results of this study illustrated that in the drop landing condition, the participants landed with greater stiffness, as exemplified by less knee flexion at impact, and greater ground reaction forces and loading rates when compared to the spike jump condition. While the vertical displacement differences might confound the results from this study, the results still suggest that when examining landing mechanics, laboratory activities such

as drop landings may not be accurately representative of an in-game activity such as landing from a functional jump task (Edwards, Steele, & McGhee, 2010).

Another basic assumption of research utilizing a drop landing task is that individual differences in performance variables, such as maximum vertical jump height, are not taken into account when determining the specific height of the drop landing task (Coffey, 2010). Maximum vertical jumps, however, do vary by individual, and it is problematic to assume that performing a 30cm drop is the same activity for individuals with significantly different maximum vertical jump heights. However, despite the problematic nature of not taking into account this performance difference during drop landing research, most studies have focused on standardizing the height rather than the activity or task (Coffey, 2010).

A common in-game activity such as a vertical jump landing (VJL) task may be able to account for individual differences in performance and does not have the concern of being a novel task like a drop landing. Landing from a vertical jump has been associated with the occurrence of noncontact ACL injuries (Besier, Lloyd, Cochrane, & Ackland, 2001; Boden, Dean, Feagin, & Garrett, 2000; Marshall, Padua, & McGrath, 2007), and is better able to reproduce neuromuscular performances that more accurately represent those that occur during normal athletic participation in a variety of sports. A VJL task should provide more accurate information on landing mechanics that may lead to a better understanding of the factors associated with noncontact ACL injuries and assist researchers in their attempt to reduce the incidence rate of these injuries.

It has also been suggested that lower extremity asymmetry may be a possible factor associated with incidents of noncontact ACL injuries (Pappas & Carpes, 2012). Clinical symmetry tests such as the functional ability test (FAT) have also been utilized in the past to

assess neuromuscular control, specifically asymmetry in grouping a control group of normal individuals and ACL deficient individuals (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998). It is unclear if an asymmetrical/symmetrical grouping from a clinical symmetry test like the FAT could be a factor involved in an individual's demonstrated landing mechanics. If a clinical symmetry test could correlate to landing mechanics associated with noncontact ACL injuries, it may tend to be a more feasible option for screening athletes than a time- and financial-intensive screening utilizing 3D motion analysis.

A previous study had attempted to examine the kinetic and kinematic differences between three landing conditions and the possible connection to a clinical assessment of asymmetry. While the kinematic variables were able to be examined, due to the design of the study involving bilateral landing on one force plate, a key predictor variable -- knee joint abduction moment -- could not be accurately recorded due to only bilateral kinetics being collected, and thus could not be examined for differences in landing condition or clinical assessment. The purpose of this current study was to follow up on this previous study, and use 3D motion analysis to compare the peak knee joint abduction moment (KAmom) during three different landing tasks and to assess possible group difference between clinically-assessed asymmetric and symmetric individuals.

Methods

Participants

Ten recreationally active males between the ages of 14 and 30 were recruited from a large public university and the surrounding community. The ten (10) male participants (5 symmetric and 5 asymmetric), had a mean age of 20.2 ± 3.6 years, a mean height of 175.3 ± 7.3 cm, a mean mass of 75.6 ± 11.4 kg, and a mean vertical jump height of 19.8 ± 5.1 inches. The symmetric and asymmetric groups were not significantly different from each other in terms of age, height, mass, and vertical jump height, and the means for each group are shown in Table 1. The inclusion criterion that was utilized consisted of recreationally active individuals between the ages of 14 and 30 years of age. For the purposes of this study “recreational athlete” was defined as being physically active at least one (1) hour three (3) days a week. The exclusion criterion that was utilized consisted of previous lower extremity surgical repair, current injury or pain affecting the lower extremity, and lower extremity injury or pain that altered participation within one month prior to testing. Previous surgery or current and/or recent injury or pain could alter the movement patterns of a subject from their normal activity, and thus negatively impact the validity of the data. Participants and/or their parent/guardian were given instructions, inclusion and exclusion requirements for the study, and the informed consent form to sign and complete. Virginia Commonwealth University Institutional Review Board reviewed this study and approved the use of human subjects.

Procedures

Participants completed a short warm-up protocol consisting of pedaling on a cycle ergometer at a self-selected light intensity for five minutes. Immediately following the warm-up, participants completed four clinical hop tests to assess their functional performance. The functional ability test (FAT) is comprised of four functional tests: a timed figure 8 (F8), a timed side hop (SH), up and down hop task (UD), and a single hop distance (HD). Based on the findings of Itoh, et al. (1998), the FAT was used as a clinical symmetry test. All four tests were completed as single-leg hopping tasks twice, once with dominant limb and once with non-dominant limb, with a one-minute rest between tasks. The order in which the tasks were performed and limb order was counterbalanced. Participants were timed for the F8, SH, and UD tasks using a handheld stop watch. For the HD task, the distance of the performed hop was manually measured and recorded for each limb. Performances for dominant and non-dominant limbs were then compared for all four tasks, and based upon the results from previous findings (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998), individuals were classified as asymmetric if limb differences for any of the four tasks were determined to be equal to or greater than 0.81s (F8), 0.72s (UD), 0.78s (SH), and 0.2m (HD). Individuals were permitted to practice each task for a maximum of two minutes before the timed or measured trial was completed. If a participant needed to restart a task due to either participant or collection error, they were given a one-minute rest period prior to restarting the task.

After completing the FAT, participants were fitted with Oxide® aqua shoes to standardize the contact surface between the foot and the landing surface. The use of aqua shoes has been previously demonstrated to be a way to standardize footwear, and has not been shown

to be risk factor for injury in biomechanical studies examining landing mechanics (Coffey, James, Sizer, & Williams, 2002; James, et al., 2001). Participants then performed three maximum one-step vertical jump attempts using the Vertec Jump Trainer (Sports Imports, Columbus, OH), which has been shown to be valid and reliable for measuring vertical jump performance (Leard, et al., 2007). The greatest height of the three jumps was designated as the individual participant's maximum vertical jump height. Anthropometric data (height, weight, and limb lengths) were also collected and recorded for all participants.

After completion of maximum vertical jump height testing, participants were prepped for completing the three landing tasks in a predetermined and counterbalanced order. The Vicon Motion Capture System™ (Vicon, Centennial, CO, USA,) utilizes sixteen near infrared tracking sensors placed bilaterally at the following locations: toe, heel, ankle, shank, knee, thigh, anterior superior iliac spine, and posterior superior iliac spine, as specified by the Vicon Plug-in Gait model (Russell, Palmieri, Zinder, & Ingersoll, 2006). A graphic detailing the placement of these markers can be seen in Figure 1. These sensors were used in a manner that has been shown to be valid and reliable in defining the lower extremity segments and motions of the knee in three dimensions during the landings via the Vicon Plug-in Gait model (Davis, Ounpuu, Tyburski, & Gage, 1991; Russell, Palmieri, Zinder, & Ingersoll, 2006).

Participants performed twelve (12) bilateral landings for each of the three experimental conditions (DL, AHDL, and VJL) onto the imbedded Bertec Force Plate, Type 4060-nonconducting (Bertec Corporation, Columbus, OH, USA) sampling at 1000 Hz. Six (6) of the bilateral landing per condition consisted of the right foot landing on the force plate and the left foot landing on the surrounding floor. The other six (6) bilateral landings were reversed, with the left foot landing on the force plate and the right foot on the surrounding floor. A 12-camera

Vicon Motion Capture System™ (100 Hz) near infrared tracking system (Vicon, Centennial, CO, USA) was utilized to track the 3D sensors and to synchronize kinetic and kinematic data. Landing in the DL condition was accomplished by having subjects step off the jumping platform and land with one foot on the force platform and the other on the surrounding ground. To simulate a game-like situation, during the landing participants were asked to catch a basketball thrown to them from a research assistant standing directly in front of them. Participants were instructed to focus on catching the basketball rather than cognitively focusing on the landing. Unsuccessful landings that included loss of balance, extreme asymmetry, dropping the basketball, or other procedural error were discarded and repeated. Landings in the AHDL condition were the same as the DL condition, except the height of the drop was set at a height equal to 80% of the participant's maximum vertical jump height, as utilized in a prior study (Coffey, James, Sizer, & Williams, 2002; James, et al., 2001). To help control for the influence of take-off foot, participants alternated the lead foot in the drop landing conditions (DL and AHDL). Landing in the VJL condition was accomplished by having the participant complete a task-oriented one-step vertical jump performance and landing with one foot on the designated force platform. Participants were asked to perform a vertical jump while reaching for a target set on the Vertec (Sports Imports, Columbus, OH) at 80% of the individual's maximum vertical jump height. Trials in which the participant was not able to reach the target or did not land with one foot on the force platform were discarded and repeated. In total, thirty-six (36) trials, twelve (12) for each task, six (6) on each side, were collected, processed, and utilized for data analysis.

Data Processing

Vicon MXControl™ software (Vicon, Centennial, CO, USA), which internally synchronized collected kinetic and kinematic data was used to process raw recorded data through the Dynamic Plug in Gait Vicon Nexus pipeline. Kinetic and kinematic data was filtered utilizing a Woltring cross-validity quintic spline routine (MSE = 20) as described previously in the literature (Woltring, 1986) and more recently validated (Molloy, Salazar-Torres, Kerr, McDowell, & Cosgrove, 2008). Filtered data was then exported from Vicon MXControl™ to Visual3D Professional v4.00.19 (C-Motion Inc., Germantown, Maryland) for post-processing analysis of individual kinetic and kinematic variables.

Peak knee abduction moment (KAmom) was defined as the peak knee abduction moment in the frontal plane from impact until 200ms after impact. Impact was defined as the point in time when the vertical ground reaction force was at least 10N (Ford, Myer, & Hewett, 2007). The timeframe, established as moment of impact to 200ms, was selected because it would encompass the timeframe in which ACL injuries have been shown to occur (Cassidy, Hangalur, Sabharwal, & Chandrashekar, 2013). Mean values for KAmom for each side were calculated for each participant in each of the three landing conditions by averaging across the six (6) trials that were performed in each landing condition per side.

Data Analysis

All statistical analysis for this study was performed using SAS version 9.4 software (SAS Corp., Cary, NC). A 2 X 3 repeated measures ANOVA (Landing Type X Symmetry Classification) with linear contrast analyses for Landtype and Symmetry were run for KAmom for the right and left side separately. ANOVA assumptions were checked for all significant models, and statistical significance was established as $\alpha = 0.05$.

Results

Peak Knee Abduction Moment

The results from the ANOVA models demonstrated that for both participants' right and left side, there were no significant differences (Right $p=.492$; Left $p=.426$) between the three landing conditions in the demonstrated KAmom. There were also no observed significant differences for KAmom for either side between the symmetric and asymmetric groups. Table 2 provides the calculated means and standard deviations for the recorded KAmom for both the right and left side. In checking the assumptions for the ANOVA, the Levene's test of equal variance found that for the right side, the displayed variance in KAmom was significantly smaller ($p=.016$) in the AHDL landing condition as compared to the two other landing conditions (DL and VJL). A smaller range in variance in the AHDL landing condition was also seen for the

left side, but was not significant ($p=.31$). These distributions of KAmom across the three landing conditions are shown for both the right and left side in Figures 2 and 3, respectively.

Discussion

As the search continues to gain a greater understanding of how athletes move when jumping and landing and what role those movements play in ACL injury risk, drop landing tasks continue to be popular research tools. The assumption for researchers is that the lower extremity landing mechanics displayed during drop landing tasks are representative of the mechanics that individuals demonstrate during actual competitions and practice when these injuries are occurring. Some of these studies have produced fairly accurate predictor models based on 3D motion analysis findings for identifying athletes at risk for noncontact ACL injuries (Hewett, et al., 2005). The insights gained from these types of studies on the mechanism of injury and prevention methods cannot be understated, but as further studies continue to expand on these findings, there is a need to assess the methodologies associated with drop landing tasks.

There are some concerns with using a task such as a set height drop landing as the primary task in the creation of a predictive model to determine which athletes are at greater risk of sustaining an ACL injury. One methodological concern has been that there is no universally recognized standard for the height of a drop landing task (Coffey, 2010). Others have also suggested that while a drop landing can be a very controlled lab activity, it may not accurately

represent a landing during a sporting competition (Edwards, Steele, & McGhee, 2010). The purpose of this study was to use 3D motion analysis to compare the KAmom during three different types of landing tasks and to assess possible group differences between clinically-assessed asymmetric and symmetric individuals.

Landing Task Differences

The results from a previous studying comparing a drop landing to a functional jump landing (Edwards, Steele, & McGhee, 2010) suggested that we would observe more stiff, and thus greater, demonstrated KAmom in the two drop landing conditions (DL and AHDL) as compared to the functional jump landing condition (VJL). The results of this current study did not demonstrate this difference, with KAmom not being statistically different in any of the three different landing conditions for either the right or left side. While Edwards, et al. (2009) attempted to control for the height of the activity, it was acknowledged that there may have been height differences between the drop landing and the functional jump that influenced the outcome. For the participants in this study, however, the heights for the landing activities were not very similar (DL=11.8in; AHDL and VJL=15.8±4.0), suggesting that there would be differences in potential energy levels between tasks, resulting in a need for the participants to alter their landing mechanics, including KAmom, to absorb this additional energy. While this was expected, the average KAmom for both the right and left side of participants were not statistically significantly different in the three landing tasks. These results for the male participants suggest that even

when differences in height and potential energy exist, there is not a difference in the demonstrated KAmom between a drop landing and a functional jumping task.

In checking the assumptions of the ANOVA for equal variance using a Levene's test, it became apparent that the variance for the KAmom variable was not equal between the three tasks, at least for the right knee, which was the dominant limb for all of the participants. Participants demonstrated on the right side significantly ($p=.016$) less variance for KAmom in the AHDL than the DL or VJL conditions. Less variance in KAmom in the AHDL condition was also demonstrated on the left side of participants, but this difference was not statistically significant. This unequal variance suggests that the performances for KAmom in the AHDL condition for at least the right side, when that is the participants' dominant side, was more consistent than in the other two tasks. While the VJL task attempts to take into account individual performance, it is expected that actual jump performance to the target may not be uniform for every trial or participant. The large range of vertical jump abilities (14in to 32in), suggests that the drop landing task from 30cm (11.8in) may functionally be a different task for individuals based on their individual vertical jump performances.

These differences in the fluctuation in jump performance during the VJL task and functional task differences based on individual jump abilities during the DL task could explain the large variance in KAmom that was seen for the right side. By adjusting the height of the activity based on individual performance and vertical jump height, while controlling for consistent task performance height, the AHDL task resulted in much more consistent KAmom performance across participants. All ten (10) participants in this study were healthy and active with no history of ACL injuries, and thus a consistent KAmom value across subjects in the AHDL suggests possible landing mechanics associated with healthy, non-injured individuals. It

is possible that individuals who display landing mechanics associated with ACL injuries, may be more easily identified using a task such as AHDL, which is able to control for individual performance differences and results in a more consistent performance (KAmom) for healthy, uninjured individuals.

Symmetry

The previous use of the FAT to identify ACL deficient individuals (Itoh, Kurosaka, Yoshiya, Ichihashi, & Mizuno, 1998) led to the hypothesis that the FAT might also be able to predict differences in lower extremity mechanics during a landing. The FAT is easy to set up and implement, and is also comparatively inexpensive. If the classification of symmetric/asymmetric could correlate to different landing mechanics, such as KAmom, it could prove to be a useful tool in understanding and preventing ACL injuries. However, the symmetric and asymmetric groups, as clinically assessed by the FAT, did not display KAmom values for either right or left side that differed between the two groups. While Itoh, et al. (1998) did not provide specifics about the athletic level of their participants, it is possible that differences existed in the recreationally active athletes utilized in this study as compared to those individuals that were used previously. If this was the case, differences in neuromuscular control may have existed based on the performance level of the participants in Itoal, et al. (1998) and those in this study. These differences may have resulted in hopping task performance differences that had a higher likelihood that participants in this study would be classified as asymmetric.

The FAT also uses specified values for maximum observed performance differences between limbs to designate symmetric/asymmetric classification. This clearly works for the population that Itoh et al. (1998) utilized, but for this participant group, there existed some wide variations in the amount of time that it took to complete some of the components of the FAT. Future studies should examine if the use of a percentage difference between limbs rather than a specified time or distance may provide greater specificity in classification of symmetry/asymmetry.

Limitations

One of the limitations of this study was the use of 3D motion analysis. 3D motion analysis is a widely utilized tool to examine how individuals move, and it provides valuable insight into movement patterns, injury prevention, and much more. It is, however, far from perfect (McGinley, Baker, Wolfe, & Morris, 2009), as it has its own limitations in regards to accuracy, and those limitations should be taken into consideration when examining 3D motion analysis results.

The examination of solely a lower extremity mechanic variable, KAmom, was also a limitation of this study. It has been suggested that even though the loading on the ACL is primarily influenced by lower extremity mechanics, it may be important to also take into account movement patterns and positioning of the trunk during landing (Wild, Steele, & Munro, 2012). While this study did not examine trunk position or movement, KAmom would be influenced by significant changes in trunk movement, as it would shift the direction of the ground reaction

force and thus the moment arm for KAmom. Based on the implications of KAmom's association with ACL injury incidence (Hewett, et al., 2005), the impact of trunk position and movement on KAmom appears to be less important than the demonstrated KAmom.

Another limitation of this study was the composition of the participants utilized based on age, gender, and athletic participation level of the participants. This age group, 14 to 30 years of age, and athletic participation level, recreationally active, were selected as criteria due to the numerous potential participants in the recruitment pool, a large public university and the surrounding community. While 14-18 year old athletes are at the highest risk for ACL injuries (Shea, Pfeiffer, Wang, Curtin, & Apel, 2004), this can also be a difficult group to recruit and obtain parental consent required for participation in such a study. Past studies have also shown that neuromuscular control strategies can change due to maturation (Oliver & Smith, 2010), and thus observed landing mechanics from this study may not be generalizable to other age groups. Selecting a single gender for participation, male athletes, provided a way to control for the influence of gender on the examined variable. Prior to assuming that the landing mechanics observed in this study are representative of more than just recreational male athletes between 14 and 30 years of age, one should examine possible differences in landing mechanics in each population based on age, gender, and activity level.

Future

Future studies are needed to further examine the landing mechanics associated with different landing conditions and how the observed differences in variance of performance in the

AHDL condition may enable greater understanding of ACL injury etiology and prevention efforts. It is also important to increase the knowledge of what role trunk position and movement play in these landing tasks, and how those factors impact lower extremity mechanics. Thus future studies should use a full-body 3D analysis model rather than just a lower extremity model to take into account trunk position changes as a possible factor in examining lower extremity mechanics. Another component that needs further investigation concerns the possible implications arising from comparing landing mechanics in a drop landing task to those of a functional task, and how the results may be impacted by the age or maturity and possible skill level of participants. A previous study utilizing the Landing Error Scoring System (LESS) to assess high-risk movement patterns found that skill level did not impact the number of errors observed (Theiss, et al., 2014). Theiss, et al. (2014) utilized college age participants, and it has been shown previously that high school-age athletes demonstrate more errors as measured by the LESS when compared to college-aged individuals (Smith, et al., 2012). It is unclear how these factors may intertwine with each other in regards to impact landing mechanics. Future studies should also examine the use of a modified FAT or other clinical assessment tool to help detect changes in landing mechanics that can currently only be assessed utilizing 3D motion analysis.

Conclusion

The use of a functional jumping task (VJL) and a drop landing task with height adjusted according to individual performance (AHDL) did not result in a statistically measured difference in KAmom. While the observed knee joint mechanics did not differ between the three landing conditions, the level of variance observed in each was not uniform, with the AHDL displaying significantly less variation. This suggests that while the use of a drop landing task is very popular for lower extremity injury prevention research, it may function as a different activity due to individuals displaying different vertical jump abilities. A VJL task, which attempts to standardize the task, may be challenging in producing consistency in height and effort. The use of an AHDL task where the activity, a drop landing, is more controlled than in a VJL and the height of the landing is adjusted based upon individual performance may produce more consistent KAmom results. Further studies are needed to examine if these results are consistent in other populations, specifically female and high school level athletes. It is also important to examine if the observed low variance for KAmom in the AHDL condition allows for easier identification of those individuals with demonstrated KAmom values outside of those observed in this study, and which may suggest they are at a higher risk of suffering an ACL injury.

Table 1. Table of demographic means for participants, both overall and in subgroups based on clinical assessment of symmetry.

Group	Height (cm)	Mass (kg)	Age (years)	Vertical Jump (inches)
Males	175.3 ± 7.3	75.6 ± 11.4	20.2 ± 3.6	19.8 ± 5.1
Male Asymmetric	177.4 ± 8.5	76.8 ± 15.1	20.6 ± 5.8	17.7 ± 2.9
Male Symmetric	173.2 ± 6.2	74.5 ± 7.8	19.8 ± 3.6	21.9 ± 6.2

Table 2. Table of means and standard deviations for peak knee abduction moment (KAmom) for participants, both overall and in subgroups based on clinical assessment of symmetry.

Group	Peak Knee Abduction Moment (Nm/kg)		
	AHDL	DL	VJL
Right	.154 ± .06	.213 ± .16	.179 ± .16
Right Asymmetric	.121 ± .03	.171 ± .19	.237 ± .15
Right Symmetric	.187 ± .06	.255 ± .14	.120 ± .16
Left	.363 ± .35	.372 ± .27	.568 ± .40
Left Asymmetric	.190 ± .05	.347 ± .23	.574 ± .40
Left Symmetric	.578 ± .46	.397 ± .33	.562 ± .45

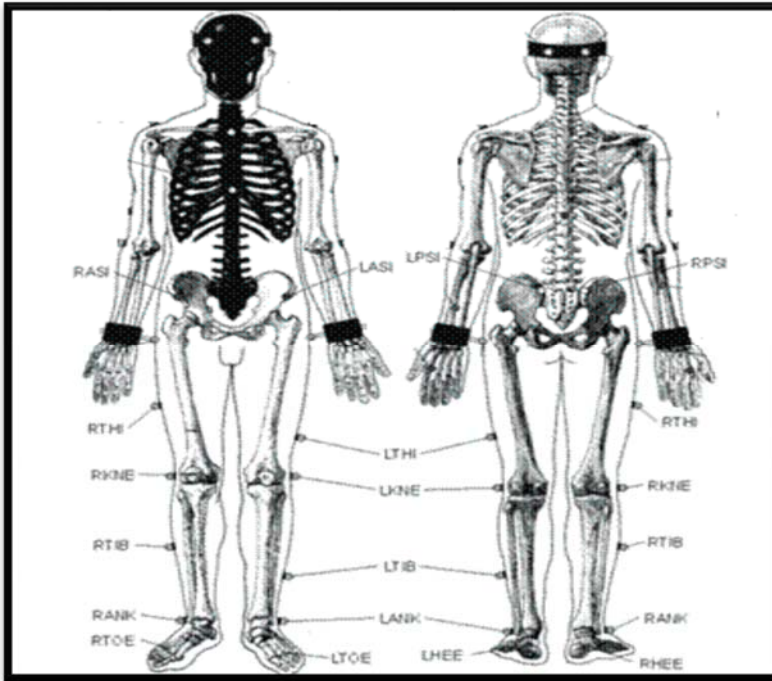


Figure 1. Visual representation of reflective marker placement for lower extremity Plug in Gait model. The graphic is adapted from the original included in the Vicon Motion Capture system™ manual.

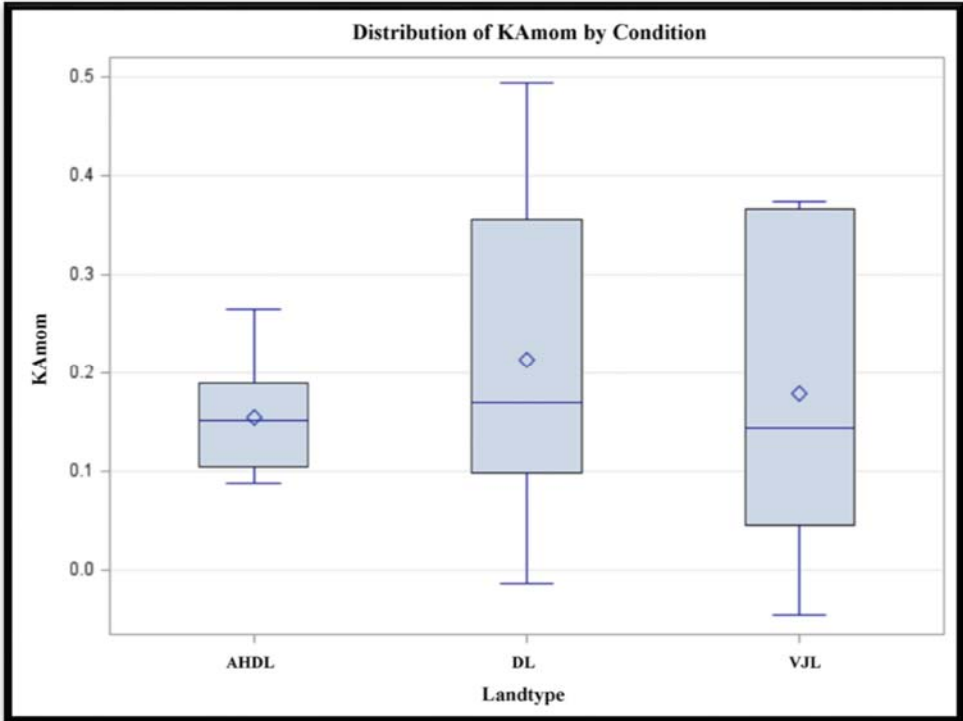


Figure 2. Boxplot of the distributions for KAmom across the three landing conditions for the right side.

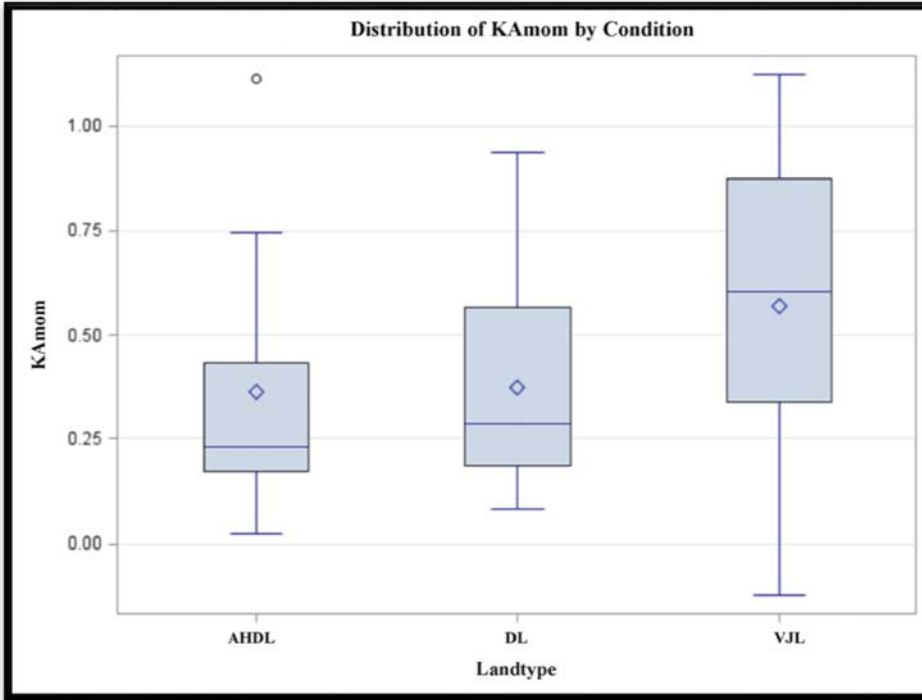


Figure 3. Boxplot of the distributions for KAmom across the three landing conditions for the left side.

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Works Cited

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Chapter 6: Conclusion of the Dissertation

The purpose of this dissertation was to compare the observed kinetic and kinematic landing mechanics between three different landing tasks, and to examine the ability of predictor models created from that 3D motion analysis data as well as a clinical screening tool to identify athletes at risk for suffering lower extremity ligamentous injuries, including ACL injuries. While drop landing tasks have been utilized in numerous research studies concerning injuries, there is a lack of standardization, and concerns have been raised about the ability of a drop landing task to replicate the landing mechanics associated with a functional task associated with athletic competition. The studies in this dissertation were designed to compare the landing mechanics between a drop landing task (DL), adjusted height drop landing task (AHDL), and a vertical jump landing task (VJL), and to examine the validity of models created based upon those performances as well as a model based upon a clinical symmetry screening tool in terms of being able to predict lower extremity ligamentous injuries.

While drop landing tasks have been a popular choice with researchers, the results from this dissertation suggest that while easy to standardize, a set height drop landing task does not produce landing mechanics identical to those from an adjusted height drop landing task or a vertical jump task (Chapters 3 and 5). Observed differences for male participants were found in both knee flexion and hip adduction angles, while for female participants, only hip adduction varied between tasks. Chapter 5 also illustrated that while differences in knee abduction moment (KAM) were not found between the three tasks, there was significantly less observed variance in the AHDL condition as compared to DL and VJL. Due to a limited number of reported injuries,

none of the predictor models based off of the 3D motion analysis or the clinical symmetry screening tool were able to produce accurate predictors of injury (Chapter 4).

Future Research

Future research is needed to gain a greater understanding of lower extremity mechanics during landing, and studies should use a full-body 3D analysis model rather than just a lower extremity model to take into account trunk position changes as a result of the observed changes in hip mechanics. Another component that needs further investigation concerns the possible implications arising from comparing landing mechanics in a drop landing task to those of a functional task, and how results may be impacted by the age or maturity and possible skill level of participants.

Concerns were also raised with the accuracy of the functional ability test (FAT) with the high school-aged participant group, as their age or maturity and possibly their skill level differences may have influenced the FAT. There is a need to either modify the FAT to use with this population group or identify a different possible screening tool that may be able to take into performance differences based on maturity and/or skill level.

The injury predictor models created in this research were not very accurate, most likely due to a small number of reported injuries. It was discussed that some of the participants in this study may have previously completed interventions or training programs designed to reduce injuries as part of team or school workout routines. Future studies should take into account the growing number of athletic programs utilizing these interventions, and collect data on

participants concerning what types of programs they have completed and the timing of those programs in relation to their participation in a research study examining performances.

Vita

Timothy George Coffey was born on April 18, 1979, in Waynesboro, Virginia, and is an American citizen. He left Wilson Memorial High School, Fishersville, VA, in 1995. In 1997, he received his Associate in Arts from Simon's Rock College of Bard, Great Barrington, MA. In 1999, he received his Bachelor of Science from the University of Maryland Baltimore County, Baltimore, MD, in Interdisciplinary Studies (combined Mechanical Engineering and Biology). In 2001, he completed his Master of Science in Biomechanics at Texas Tech University, Lubbock, TX. He has been employed by Virginia Commonwealth University since 2003 in various capacities within the Division of Student Affairs.