

To the Graduate Council:

I am submitting here with a dissertation written by Jeremiah Jackson Tate entitled " The Effect of Technique Instruction on Biomechanical Risk Factors Associated with Anterior Cruciate Ligament Injury in Female Recreational Athletes". I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy with a major in Exercise and Sport Sciences.

Clare E. Milner, Major Professor

We have read this dissertation
and recommend its acceptance:

Songning Zhang

Jeffrey T. Fairbrother

Russell L. Zaretski

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the
Graduate School

(Original Signatures are on file with official student records.)

**The Effects of Technique Instruction on
Biomechanical Risk Factors Associated with ACL
Injury Risk in Female Recreational Athletes**

A Dissertation Presented for
the Doctor of Philosophy
Degree

The University of Tennessee, Knoxville

Jeremiah Jackson Tate

December 2010

ACKNOWLEDGEMENTS

I thank my wife, Amanda, for her relentless support during the past four years and throughout my graduate school training. I could not have achieved my dream of becoming a college professor without her.

I express my sincere appreciation and gratitude to Dr. Milner for her steady guidance as my advisor at the University of Tennessee. Her expertise in biomechanics and research had greatly impacted my future as a teacher, researcher, and practicing clinician.

I also want to thank Dr. Fairbrother for his love for teaching. His course in motor learning not only directed me to my research question, but also taught me many valuable lessons regarding the "art of teaching".

Additionally, I thank my other committee members, Dr. Zhang and Dr. Zaretzki, for their contribution to my academic preparation and respective roles in preparing this dissertation. I also thank the physical therapy faculty at the University of Tennessee at Chattanooga. Their continued support played a vital role in my fulfillment of this degree.

Special thanks to Carolyn Westlake, a fellow grad student, for her assistance in data processing.

ABSTRACT

Background: Epidemiological studies have demonstrated higher ACL injury rates in female athletes when compared to males involved in the same sport. A recent meta-analysis of ACL injury prevention programs found that technique training was a common component of programs that were successful in reducing ACL injury.

Purpose: The primary purpose was to determine the immediate and long-term effects of technique training aimed at minimizing medial knee displacement during jump-landings in female recreational athletes. The secondary purpose was to determine if any transfer of skill occurred as a result of our technique training.

Study Design: Controlled laboratory study.

Methods: A total of 26 participants who presented with medial knee displacement during a basketball rebound screening task completed the study protocol. Participants were randomly assigned to two groups (experimental and control groups, 13 each). The experimental groups received jump landing instructions aimed at minimizing medial knee displacement. The control group received "sham" training consisting of jump training for maximum height. Baseline motion analyses of participants performing a basketball rebound task were performed prior to participants receiving technique training. Immediate and delayed retentions tests were performed after the initial instructional session and after home-based training. Additionally, motion analyses were also performed on

a stop-jump task during the baseline assessment and the delayed retention test to help in determining if any transfer occurred.

Results: The initial instructional session resulted in increased knee excursion and reduced peak knee adduction moments in the experimental group.

Following home-based training, the experimental group continued to exhibit increased knee excursion along with decreased landing forces. No evidence of transfer was present following the initial training session or after home-based training.

Conclusion: Our jump training instructions led to temporary changes, most notably increased knee excursion about the sagittal plane. No transfer of skill occurred as a result of our training.

Clinical Relevance: Technique training instructions aimed at reducing medial knee displacement resulted in increased sagittal plane motion, but were unable to minimize medial knee displacement. ACL injury prevention programs may need to include a variety of drills, tasks, and sport-specific movements.

TABLE OF CONTENTS

Chapter	Page
CHAPTER I: Introduction	1
Purpose	7
Research Hypotheses	8
Phase One	8
Phase Two	9
Definitions	11
Assumptions	11
Delimitations	12
Limitations	12
Independent Variable	13
Dependent Variables	13
CHAPTER II: Literature Review	14
Introduction	14
ACL Injuries	14
Incidence and Costs	14
Mechanisms of ACL Injury	16
Risk Factors of Noncontact ACL Injuries	17
Sagittal Plane Kinematics and Kinetics	18
Frontal Plane Kinematics and Kinetics	20
Summary	21

ACL Injury Prevention Programs	22
Technique Training Studies: An assessment of methodology related to known principles of motor skill instruction.....	25
Preparing the Stage for Motor Learning.....	26
Instructions	27
Demonstrations.....	30
Feedback.....	32
Strengths	36
Limitations.....	37
Future Research	37
Biomechanical Rationale for Kinetic Outcome Measures.....	39
Peak Internal Knee Adduction Moment	40
Peak Internal Knee Extension Moment.....	44
Peak Vertical Ground Reaction Force	45
Summary	46
CHAPTER III: Materials and Methods.....	48
Participants	48
Screening and Maximum Vertical Jump Testing	49
Equipment	52
Baseline Testing Protocol.....	53
Jump Training Protocol	54
Phase One.....	54
Phase Two.....	57

Data Reduction.....	59
Statistical Analysis.....	61
Phase One.....	61
Phase Two.....	62
CHAPTER IV: Results	64
Participants	64
Countermovement Jump (Retention Tests): Phase One.....	66
Frontal Plane Variables	66
Sagittal Plane Variables.....	68
Ground Reaction Force Variable	69
Stop-jump Task (Transfer Test): Phase One.....	71
Approach Speed	71
Frontal Plane Variables	71
Sagittal Plane Variables.....	71
Ground Reaction Force Variable	73
Countermovement Jump (Retention Tests): Phase Two.....	73
Frontal Plane Variables	73
Sagittal Plane Variables.....	75
Ground Reaction Force Variable	77
Stop-jump Task (Transfer Test): Phase Two.....	77
Approach Speed	77
Sagittal Plane Variables.....	79
Ground Reaction Force Variable	79

CHAPTER V: Discussion	80
Phase One	82
Frontal Plane Effects	82
Sagittal Plane Effects.....	84
Ground Reaction Force Effects.....	85
Transfer Test	87
Phase Two	88
Frontal Plane Effects	89
Sagittal Plane Effects.....	91
Ground Reaction Force Effects.....	92
Transfer Test	94
Motor Learning Principles.....	94
Transfer.....	97
Performance.....	98
Limitations	98
Future Directions	99
Conclusion	101
LIST OF REFERENCES.....	102
APPENDICES.....	116
Appendix A. IRB Form for Control Group.	117
Appendix B. IRB Form for Experimental Group.....	120
Appendix C. Activity Questionnaire	123
Appendix D. Physical Activity Readiness Questionnaire	124

Appendix E. Exploder System	125
Appendix F. Marker set	126
Appendix G. Countermovement-Jump Task	127
Appendix H. Stop-Jump Task.....	128
Appendix I. Diagram of overall data collection process.	129
Appendix J. Jump Instructions for Experimental Group.....	130
Appendix K. Jump Instructions for Control Group.	132
Appendix L. Demographic data values for each participant that completed the study protocol.	133
Appendix M. Individual data values for dependent variables.....	134
Appendix N. ANOVA Tables: Countermovement Jump, Phase One.....	155
Appendix O. ANOVA Tables: Stop-jump Task, Phase One.	158
Appendix P. ANOVA Tables: Countermovement Jump, Phase Two.....	160
Appendix Q. ANOVA Tables: Stop-jump Task, Phase Two.	162
Appendix R. Group * Time Tables: Countermovement Jump, Phase One..	163
Appendix S. Group * Time Tables: Stop-jump Task, Phase One.	165
Appendix T. Group * Time Tables: Countermovement Jump, Phase Two. .	167
Appendix U. Group * Time Tables: Stop-jump Task, Phase Two.....	169
Vita.....	171

LIST OF TABLES

Table	Page
Table 1. Participants' history of sports.	65
Table 2: Mean (SD) for Age, Height, Weight, BMI*, and Maximum Vertical Jump Height for Experimental and Control Groups.	66
Table 3: Means (SD), Effect Sizes and Percentage Changes for Primary Variables for Countermovement Jump, Phase One.....	67
Table 4: Means (SD) for Peak Hip Flexion and Ankle Dorsiflexion Angles for Countermovement Jump, Phase One.....	70
Table 5: Means (SD), Effect Sizes and Percentage Changes for Primary Variables for Stop-jump task, Phase One.....	72
Table 6: Means (SD) for Approach Speed (m/s) for Stop-jump Task, Phase One.	73
Table 7: Means (SD), Effect Sizes and Percentage Change for Primary Variables for Countermovement Jump, Phase Two.....	74
Table 8: Means (SD) for Peak Hip Flexion and Ankle Dorsiflexion Angles for Countermovement Jump, Phase Two.....	76
Table 9: Means (SD), Effect Sizes and Percentage Changes for Primary Variables for Stop-jump Task, Phase Two.....	78
Table 10: Means (SD) for Approach Speed (m/s) for Stop-jump Task, Phase Two.....	79

CHAPTER I: Introduction

An estimated 200,000 people will suffer an anterior cruciate ligament (ACL) injury each year (Marshall, Padua et al., 2007). Epidemiological studies have demonstrated higher ACL injury rates in female collegiate athletes when compared to males involved in the same sport (Arendt and Dick, 1995; Arendt, Agel et al., 1999; Agel, Arendt et al., 2005). The majority of ACL injuries have been attributed to noncontact mechanisms during sudden decelerations and jump-landings (Boden, Dean et al., 2000; Olsen, Myklebust et al., 2004). Risk factors associated with noncontact ACL injuries have been classified as environmental, anatomical, hormonal, or biomechanical (Griffin, Agel et al., 2000; Griffin, Albohm et al., 2006). Of these four risk factors, biomechanical factors have received the most attention since they are likely the easiest to change through neuromuscular training (Agel, Olson et al., 2007).

In general, biomechanical studies have demonstrated that internal extension and adduction moments of the knee most likely play a significant role in noncontact ACL injury mechanisms (Chappell, Yu et al., 2002; Hewett, Myer et al., 2005; McLean, Walker et al., 2005). The debate still remains on whether sagittal or frontal plane loading plays a larger role in noncontact ACL injuries (McLean, Andrich et al., 2005; van den Bogert and McLean, 2006). However, researchers do agree that movement patterns that result in an increased combination of sagittal and frontal plane loading appear to increase risk of ACL injury (Griffin, Albohm et al., 2006). Therefore, any significant decrease in one or both of these variables most likely would result in a significant decrease in ACL

loading. Likewise, researchers have also demonstrated that females who sustained ACL injury landed with greater maximum knee abduction angles during jump-landings compared to females who did not sustain injury (Hewett, Myer et al., 2005). A reduction in dynamic knee valgus may also be beneficial in reducing ACL injury risk. Additionally, the reduction of vertical ground reaction forces encountered during jump landings should also help reduce the risk of ACL injury. McNair and Marshall (McNair and Marshall, 1994) demonstrated that vertical ground reaction forces and tibial accelerations associated with jump landings were positively correlated. They suggested that a reduction in impact loads (i.e., ground reaction forces) during the landing of a jump might also result in an overall decrease in knee loading. In addition, Onate et al. also examined the amount of knee excursion during the landing, hypothesizing that a greater amount of knee excursion may be beneficial in reducing knee injury risk (Onate, Guskiewicz et al., 2005). Accordingly, technique training should attempt to alter jump-landing techniques in a manner that reduces the overall loading of the knee joint in hopes of reducing ACL injury rates.

Several neuromuscular training programs have been developed to address the ACL injury epidemic in females and provide a glimpse of hope in reducing knee injuries, particularly those involving the ACL (Hewett, Lindenfeld et al., 1999; Myklebust, Engebretsen et al., 2003; Mandelbaum, Silvers et al., 2005). These programs were performed during the preseason (Hewett, Lindenfeld et al., 1999; Myklebust, Engebretsen et al., 2003; Mandelbaum, Silvers et al., 2005) and some programs were continued at a lower frequency

throughout the season (Myklebust, Engebretsen et al., 2003; Mandelbaum, Silvers et al., 2005). Each of these programs have included multiple training modalities. For example, the programs developed by Hewett et al. (Hewett, Stroupe et al., 1996; Hewett, Lindendorf et al., 1999), Mandelbaum et al. (Mandelbaum, Silvers et al., 2005), and Myklebust et al. (Myklebust, Engebretsen et al., 2003) each involved some combination of plyometric, strength, technique, and balance training. However, the comprehensive nature of these ACL injury prevention programs might act as a deterrent to some coaches due to large time commitments (Hewett, Shultz et al., 2007). In addition, the high volume in training might actually increase the chance of injury, especially for populations that have an elevated injury risk (e.g., adolescent female athletes) (Hewett, Shultz et al., 2007). Therefore, researchers have suggested that future investigations should analyze the individual contribution of each training modality with a goal of improving the overall efficiency of ACL injury prevention programs (Hewett, Shultz et al., 2007; Herman, Onate et al., 2009).

A recent meta-analysis of ACL injury prevention programs found that technique training was a common component of programs that were successful in reducing injury (Hewett, Ford et al., 2006). Although no study has examined the effects of technique training alone on the reduction of knee injuries, there is evidence that technique training can alter participants' jump-landing styles in ways that are currently thought to reduce the risk of knee injury (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000; Onate, Guskiewicz et al., 2001; Onate, Guskiewicz et al., 2005; Cronin, Bressel et al., 2008; Mizner, Kawaguchi

et al., 2008). Previous technique training studies have primarily used verbal instructions to alter lower extremity movement patterns during jump-landings (Gervais, 1997; McNair and Prapavessis, 1999; McNair, Prapavessis et al., 2000; Onate, Guskiewicz et al., 2001; Cowling, Steele et al., 2003; Prapavessis, McNair et al., 2003; Onate, Guskiewicz et al., 2005; Cronin, Bressel et al., 2008; Mizner, Kawaguchi et al., 2008). Prapavessis and McNair (Prapavessis and McNair, 1999) and McNair et al. (McNair, Prapavessis et al., 2000) have tested the effects of verbal instruction on decreasing landing forces. In their studies, participants were instructed “to land on the balls of their feet with bent knees and upon landing lower their heels slowly to the ground while bending their knee well after landing” (McNair and Prapavessis, 1999; McNair, Prapavessis et al., 2000). Post-tests performed immediately following verbal instruction demonstrated transient reductions in peak vertical ground reaction forces during the jump-landings. One could argue that their verbal instruction contained too much information, which could have impeded long-term motor learning (Schmidt and Lee, 2005). It has been recommended that only one or two of the key elements associated with the skill should be delivered to the learner during the acquisition phase (i.e., practice) (Schmidt and Lee, 2005). Future studies using verbal instructions may improve motor learning by minimizing the number of salient points to avoid overloading the learner’s attentional capacity.

Instructors must also consider where they direct the learner’s attentional focus when providing verbal cues. Researchers have typically classified the direction of a learner’s attention focus as either external or internal. An external

focus directs the learner's attention to the movement effect on the environment, while an internal focus directs the learner's attention to the movement themselves (Wulf and Su, 2007). Several motor behavior studies have demonstrated that an external focus results in better motor skill performance and learning compared to an internal focus (Wulf, McNevin et al., 2001; McNevin, Shea et al., 2003; Wulf, Weigelt et al., 2003; Wulf and Su, 2007). Researchers have explained the positive benefits of an external focus with the constrained action hypothesis (Wulf, McNevin et al., 2001; McNevin, Shea et al., 2003). In short, an external focus allows a learner to rely more on automatic motor processes, which facilitate performance and learning. In contrast, an internal focus, which directs the learner towards the movement, constrains the motor system and disrupts automatic processes.

Feedback has been regarded as the single most important variable for motor learning with the exception of practice (Schmidt and Lee, 2005). Feedback is defined as the information that occurs as a result of a motor performance and is typically classified as either inherent feedback or augmented feedback (Rose and Christina, 2006). Inherent feedback occurs as a natural result of the movement and is provided by one's sensory mechanisms, such as vision, audition, and somatosensation. Conversely, augmented feedback is provided by an external source, such as verbal feedback from a coach, and is complementary to the already present inherent feedback. Several technique training studies have assessed the potential benefits of inherent feedback as a method of providing participants with information about their jump-landing

performance (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000; Onate, Guskiewicz et al., 2001). In these studies, participants were instructed to use available sensory information from baseline jump-landing trials in efforts to decrease vertical ground reaction forces (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000; Onate, Guskiewicz et al., 2001). Overall, the results of these studies have indicated that inherent feedback alone was inferior to other instructional interventions, such as verbal instructions (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000) and videotape feedback (Onate, Guskiewicz et al., 2001), for improving motor performance. Based on these findings, participants of jump-training programs may have difficulty in understanding how to best use their available inherent feedback during training.

Videotape replay is a common method used by coaches and clinicians to provide augmented feedback. Onate et al. (Onate, Guskiewicz et al., 2001; Onate, Guskiewicz et al., 2005) and Herman et al. (Herman, Onate et al., 2009) assessed the effectiveness of videotape feedback in their technique training studies. In their studies, participants were provided with videotape replays of their baseline jump-landings prior to jump-landing practice. Additionally, a clinician provided participants with verbal cues regarding specific elements of the jump-landing during the viewing of the video replay. Results of these studies suggested that the use of videotape feedback was an effective means of providing motor skill instruction for the learning of jump-landings. Despite the apparent effectiveness of videotape feedback, it has yet to be included in neuromuscular training programs. This may be due to time constraints

associated with the set-up and viewing of the videotape. Others have suggested that a mirror may be a useful method to provide participants of jump-training programs with augmented feedback (Myer, Ford et al., 2004), but its effectiveness has yet to be explored by researchers.

In a recent study, Herman et al. (Herman, Onate et al., 2009) pointed out the importance of demonstrating whether or not newly acquired skills that are developed as a result of technique training results in transfer. Schmidt and Lee define transfer "as the gain (or loss) in proficiency in one skill as a result of practice on some other skill" (Schmidt and Lee, 2005). Several neuromuscular training programs use a variety of drills and tasks so that participants are able to practice their jump-landing in different situations (Hewett, Stroupe et al., 1996; Mandelbaum, Silvers et al., 2005). Therefore, it would be helpful to determine whether or not technique training can result in transfer. If so, then these neuromuscular training programs may be able to reduce the number of tasks in efforts to improve the overall efficiency of the program.

Purpose

The primary purpose of this dissertation was to examine the effects of jump-landing training procedures aimed at improving lower extremity kinetics and kinematics in high-risk females during tasks associated with ACL injury risk. Specifically, this dissertation sought to identify whether the jump-landing training procedures are capable of resulting in permanent changes (i.e., motor learning) in lower extremity kinetics during jump-landing and deceleration tasks. Furthermore, this dissertation sought to determine if any changes that were a

result of the jump-training procedures resulted in transfer to a similar jump-landing task. The training procedures consisted of verbal instructions that focused the participants' attention on an external focus aimed to improve the frontal plane alignment of the participants' knees. In addition, a full-length mirror was used during practice jumps to provide participants with augmented feedback regarding the position of their lower extremities during the jump-landing.

This dissertation consisted of two phases, phase one and phase two. During phase one, The initial instructional session determined whether our jump-landing training procedures used in the program result in short-term learning and transfer effects. Follow-up testing after home-based training based on our jump-landing training procedures determined whether any short-term changes were preserved and resulted in any new additional changes as the result of increased practice.

Research Hypotheses

Phase One

1. During the immediate and delayed retention tests (i.e., countermovement jump task), participants in the experimental group, compared to the control group, will land with decreased:
 - 1.1 peak vertical ground reaction force
 - 1.2 peak internal knee extension moment
 - 1.3 peak internal knee adduction moment
 - 1.4 peak knee abduction angle.....compared to baseline.

2. During the immediate and delayed retention tests (i.e., countermovement jump task), participants in the experimental group, compared to the control group, will land with increased:

- 2.1 knee excursion

-compared to baseline.

3. During the transfer test (i.e., stop-jump task) participants in the experimental group, compared to the control group, will land with decreased:

- 3.1 peak vertical ground reaction force

- 3.2 peak internal knee extension moment

- 3.3 peak internal knee adduction moment

- 3.4 peak knee abduction angle

-compared to baseline.

4. During the transfer test (i.e., countermovement jump task), participants in the experimental group, compared to the control group, will land with increased:

- 4.1 knee excursion

-compared to baseline.

Phase Two

5. During the immediate and delayed retention tests following home-based training (i.e., countermovement jump task), participants in the experimental group, compared to the control group, will land with decreased:

5.1 peak vertical ground reaction force

5.2 peak internal knee extension moment

5.3 peak internal knee adduction moment

5.4 peak knee abduction angle

.....compared to baseline.

6. During the immediate and delayed retention tests following home-based training (i.e., countermovement jump task), participants in the experimental group, compared to the control group, will land with increased:

6.1 knee excursion

.....compared to baseline.

7. During transfer test following home-based training (i.e., stop-jump task), participants in the experimental group, compared to the control group, will land with decreased:

7.1 peak vertical ground reaction force

7.2 peak internal knee extension moment

7.3 peak internal knee adduction moment

7.4 peak knee abduction angle

.....compared to baseline.

8. During the delayed transfer test following home-based training (i.e., countermovement jump task), participants in the experimental group, compared to the control group, will land with increased:

8.1 knee excursion

.....compared to baseline.

Definitions

1. Healthy – Participants were considered "healthy" if they did not have a history of ACL injury, lower extremity fracture or surgery, lower extremity injury in the past six months which limited activity levels for more than 2 weeks, and also answered "no" to all seven questions on the physical activity readiness questionnaire.
2. Recreational athlete – A recreational athlete was defined as a person who currently participates in a sport involving jumping (e.g., basketball, soccer, volleyball) and previously participated in a sport involving jumping at a high school varsity level.
3. Landing phase of countermovement jump – The landing phase began when the participant's feet contacted the ground and ended at maximum knee flexion.
4. Medial knee displacement - Medial knee displacement was defined as the midpoint of the patella passing medial to the big toe.

Assumptions

1. The criterion used to indicate medial knee displacement is a valid and reliable measure.
2. A Vertec standiometer is a valid and reliable measure of maximum vertical jump height.
3. The jump-landing training procedures provided to participants are appropriate for eliciting desired changes in landing style.

Delimitations

1. The participants in this study will consist of females between the ages of 18-30.
2. All participants in this study will be recreationally active.
3. All participants in the training aspect of the study will demonstrate medial knee displacement during the landing phase following a countermovement jump.
4. Participants will have no known lower extremity injuries that will limit their ability to perform the tasks required of this study.
5. Participants will not have participated in an ACL injury prevention program.
6. Movement tasks will be limited to the countermovement jump and stop-jump task.
7. All analyses will be performed on the leg presenting with the most medial knee displacement.

Limitations

1. Results of this study will be limited to female recreational athletes between the ages of 18-30 who exhibit medial knee displacement during jump landings.
2. All movement tasks will be performed in a laboratory setting. The movements, therefore, will not be the same as sport-specific movements encountered during ACL injury.

3. The results of this study will be limited to the following movement tasks:
countermovement jump and stop-jump task.

Independent Variable

1. Jump-landing training protocol

Dependent Variables

1. Peak vertical ground reaction force
2. Peak internal knee extension moment
3. Peak internal knee adduction moment
4. Knee excursion
5. Peak knee abduction angle

CHAPTER II: Literature Review

Introduction

The primary goal of this dissertation is to examine the effects of jump-landing training procedures aimed at improving lower extremity kinetics in high-risk females during tasks associated with ACL injury risk. This review of the literature will provide: 1) a background on the incidences, costs, and mechanisms of ACL injury, 2) a review of risk factors associated with noncontact ACL injury to include a detailed discussion of biomechanical risk factors associated with altered movement patterns, 3) a review of neuromuscular training programs that have resulted in reduced ACL injury rates, 4) a review experimental procedures of technique training studies that used instructions, demonstrations, and feedback to determine how well ground their methods were in terms of known principles of motor skill instruction, and 5) a biomechanical rationale for each primary kinetic variable that will be included in this dissertation.

ACL Injuries

Incidence and Costs

An estimated 200,000 people in the US will suffer an ACL injury each year (Marshall, Padua et al., 2007). Norwegian (Granat, Bahr et al., 2008) and Danish (Lind, Menhert et al., 2009) knee registries have indicated that the overall incidences of ACL reconstructive surgery were 34 and 38 per 100,000 citizens, respectively. These incidence rates applied to the current US population would suggest that over 100,000 ACL reconstructive surgeries are performed each year. This estimation is in agreement with data from the National Hospital

Discharge Survey, which indicated that 100,000 ACL reconstructions were performed during 1996 (USDHHS, 1996). The estimated cost associated with orthopaedic care and rehabilitation following ACL injury has been approximated at \$17,000 per patient (Hewett, Lindenfeld et al., 1999), which would amount to over \$1.7 billion annually. ACL injury also results in temporary disability related to loss of time from work, school, and sports (Griffin, Albohm et al., 2006). Furthermore, permanent disability related to the development of posttraumatic degenerative joint disease in knees is another long-term consequence of ACL injury (Griffin, Albohm et al., 2006).

Epidemiological studies have demonstrated statistically significant higher ACL injury rates in collegiate females when compared to males involved in the same sport (Arendt and Dick, 1995; Arendt, Agel et al., 1999; Agel, Arendt et al., 2005). In a recent systematic review of studies involving incidence rates of ACL injuries examining specific sporting subpopulations, researchers concluded that females were 1.5-4.6 times more likely to suffer an ACL injury compared to males (Marshall, Padua et al., 2007). Data from the Danish knee ligament reconstruction registry indicated that a greater proportion of females under the age of 25 underwent primary ACL reconstruction compared to males (Lind, Menhert et al., 2009). Therefore, researchers have focused on the development of ACL injury prevention programs aimed at decreasing the incidence of ACL injuries, especially in female athletes (Hewett, Lindenfeld et al., 1999; Myklebust, Engebretsen et al., 2003; Mandelbaum, Silvers et al., 2005).

Mechanisms of ACL Injury

Several studies have investigated the mechanisms of ACL injuries in various sports (Boden, Dean et al., 2000; Olsen, Myklebust et al., 2004; Krosshaug, Nakamae et al., 2007). These studies have used either retrospective interviews (Boden, Dean et al., 2000; Olsen, Myklebust et al., 2004) or qualitative video analyses (Boden, Dean et al., 2000; Olsen, Myklebust et al., 2004; Krosshaug, Nakamae et al., 2007) to determine the various mechanisms of injury. Results have demonstrated that the majority of ACL injuries (72%) occurred without direct contact to the knee (Boden, Dean et al., 2000; Krosshaug, Nakamae et al., 2007). ACL injuries that occur without direct contact to the knee have typically been classified as noncontact, while injuries involving direct contact have been classified as contact. However, a recent conference theme emerged suggesting that researchers classify ACL injuries as either resulting from direct contact, indirect contact, or noncontact (Shultz, Schmitz et al., 2008). Evidence supporting this newer classification was provided in a recent video analysis study of ACL injuries (Krosshaug, Nakamae et al., 2007). In this study, researchers found that 50% of females who suffered ACL injuries were perturbed just prior to their injury. Shultz et al. (Shultz, Schmitz et al., 2008) suggested that risk factors might differ between athletes who suffer noncontact ACL injuries vs. athletes who suffer ACL injury as a result of indirect contact.

Researchers have found that the majority of noncontact ACL injuries occurred either during a sudden deceleration associated with a change in direction (e.g., plant-and-cut movement) or during a jump-landing (Boden, Dean

et al., 2000; Olsen, Myklebust et al., 2004). Qualitative video analyses of noncontact ACL injuries have demonstrated that most knees were close to full extension at the time of injury (Boden, Dean et al., 2000; Olsen, Myklebust et al., 2004). Moreover, these analyses have also demonstrated that the injured knee undergoes a forceful valgus with either internal or external rotation of the leg (Olsen, Myklebust et al., 2004). Based on these findings, ACL injuries appear to be associated with sudden deceleration tasks or jump landings with the knee in a relatively extended position. Furthermore, multi-plane loading (i.e., valgus and external/internal rotation) of the knee also appears to be associated with ACL injuries.

Risk Factors of Noncontact ACL Injuries

Risk factors associated with noncontact ACL injury can be classified into one of four categories: environmental, anatomical, hormonal, or neuromuscular (Griffin, Agel et al., 2000; Griffin, Albohm et al., 2006). Environmental factors include meteorological conditions, surface and shoe types and their associated interactions, and protective equipment (e.g., knee braces). Anatomical risk factors consist of lower extremity alignment measurements (e.g., Q-angle, knee valgus, foot pronation), body mass index, notch size, and ACL geometry. Hormonal factors are related to the role of sex hormones on ACL mechanical behavior and ACL injury risk. Neuromuscular risk factors consist of altered movement and activation patterns that exist between genders (e.g., knee joint kinematics/kinetics and muscle activation patterns) during movement tasks linked to ACL injury. Researchers agree that biomechanical risk factors appear to play

the primary role in the higher incidence of ACL injuries seen in females (Griffin, Agel et al., 2000). Therefore, biomechanical risk factors have been a primary focus of researchers when designing ACL injury prevention programs.

The following sections highlight the biomechanical studies that have assessed gender differences in the sagittal and frontal planes during movement tasks involving sudden decelerations, pivoting, and jump-landings.

Sagittal Plane Kinematics and Kinetics

Malinzak et al. (Malinzak, Colby et al., 2001) found that females exhibited less knee flexion during the stance phase for side-cutting and cross-cutting tasks compared to age-matched males. These differences between females and males' knee flexion angles during side-cutting increased during stance with females demonstrating approximately 15° less knee flexion during the latter part of stance. Females also demonstrated 8° less knee flexion during the cross-cutting task and maintained this difference throughout stance. In another study, Chappell et al. (Chappell, Yu et al., 2002) found statistically significant gender differences in sagittal plane joint kinetics during the landing phase of a stop-jump task. Their results indicated that females exhibited larger internal knee extension moments and significantly larger peak proximal tibial anterior shear forces. Mclean et al. (McLean, Walker et al., 2005) also noted that these gender differences were also present at the hip. In their study, females exhibited a more extended posture of the hips and knees compared to males during a shuttle-run task.

Other biomechanical studies have failed to demonstrate differences in sagittal plane knee kinematics and kinetics (Ford, Myer et al., 2005; Kernozek, Torry et al., 2005; Nagano, Ida et al., 2007). Ford et al. (Ford, Myer et al., 2005) did not find any significant gender differences in knee flexion angles at initial contact or at maximum knee flexion during an unanticipated stop-jump task. Likewise, Kernozek et al. (Kernozek, Torry et al., 2005) did not find any significant differences in sagittal plane hip and knee angles between genders during a drop landing. However, they did find that females landed with greater peak ankle dorsiflexion angles. Similarly, Nagano et al. (Nagano, Ida et al., 2007) did not find any gender differences in knee flexion during a single-legged landing.

The lack of significant differences in sagittal plane kinematics and kinetics in these studies might be due to differences in the studies' participants. For example, Ford et al. (Ford, Myer et al., 2005) studied movement patterns of middle and high school-age athletes. Their lack of significant findings may be related to the participant's age. Studies that observed significant differences in sagittal plane knee flexion all assessed young adults (i.e., university recreational and competitive athletes) (Malinzak, Colby et al., 2001; Chappell, Yu et al., 2002; McLean, Walker et al., 2005). Differences in movement tasks may be another reason for lack of agreement between studies. McLean et al. (McLean, Walker et al., 2005) observed significant gender differences in sagittal plane hip and knee mechanics during a shuttle-run task. However, these sagittal plane differences were not observed in the same group of participants during the

performance of a side-step and side jump tasks. Based on this study, gender differences in lower extremity movement patterns may not occur in all jumping and cutting tasks.

Frontal Plane Kinematics and Kinetics

Several studies have found gender differences in frontal plane kinematics and kinetics during a variety of tasks, including a shuttle run (McLean, Walker et al., 2005), side-step (Malinzak, Colby et al., 2001; McLean, Walker et al., 2005), cutting (Malinzak, Colby et al., 2001; Ford, Myer et al., 2005; McLean, Walker et al., 2005), and stop-jump tasks (Chappell, Yu et al., 2002; Ford, Myer et al., 2005), and double (Ford, Myer et al., 2003; Kernozek, Torry et al., 2005) and single-legged jump-landings (Ford, Myer et al., 2006; Pappas, Hagins et al., 2007). These studies determined that females were in a position of greater knee abduction at initial contact (McLean, Walker et al., 2005) and demonstrated greater peak knee abduction angles (Ford, Myer et al., 2003; Ford, Myer et al., 2005; Kernozek, Torry et al., 2005; McLean, Walker et al., 2005; Ford, Myer et al., 2006; Pappas, Hagins et al., 2007) during the stance or landing phase of the task. Malinzak et al. (Malinzak, Colby et al., 2001) found that females positioned their knee in more abduction throughout the entire stance for side-step and cutting tasks. In addition, Chappell et al. (Chappell, Yu et al., 2002) found greater peak external knee abduction moments during the landing phase of a stop-jump task. Similarly, Kernozek et al. (Kernozek, Torry et al., 2005) found a smaller internal knee varus moment at peak knee abduction angle during double-legged jump-landings. Researchers have also found greater frontal plane

excursion at the hip (Ford, Myer et al., 2006) and ankle (Kernozek, Torry et al., 2005; Ford, Myer et al., 2006) during jump-landings.

The results of these studies suggest that female athletes, compared to males, tend to exhibit greater amounts of knee abduction during the stance and landing phases of cutting and jump-landing tasks, respectively. Additionally, female athletes appear to undergo greater loading of the knee in the frontal plane. Recent studies suggest that the hip and ankle joint mechanics may play a role in the gender differences observed at the knee.

Summary

Numerous studies over the past decade have demonstrated significant kinematic and kinetic differences between males and females in tasks associated with ACL injury. Some researchers suggest that females have a tendency to exhibit a more erect posture (i.e., less hip and knee flexion), while others do not. It may be that gender differences in the sagittal plane depend on variables such as the age of the athlete and the movement task being observed. There appears to be a greater consensus that female athletes undergo greater movement and loading in the frontal plane during cutting and jump-landing tasks compared to their male counterparts. Altogether, these gender differences in the sagittal and frontal planes have been suggested as potential mechanisms for ACL injury.

ACL Injury Prevention Programs

Several neuromuscular training programs have been successful in reducing knee injuries, particularly those involving the ACL (Hewett, Lindenfeld et al., 1999; Myklebust, Engebretsen et al., 2003; Mandelbaum, Silvers et al., 2005). Each of these programs have included multiple training components. For example, the programs developed by Hewett et al. (Hewett, Stroupe et al., 1996; Hewett, Lindenfeld et al., 1999), Mandelbaum et al. (Mandelbaum, Silvers et al., 2005), and Mykelbust et al. (Myklebust, Engebretsen et al., 2003) each involved some combination of plyometric, strength, technique, and balance training.

The prevention program developed by Hewett et al. (Hewett, Lindenfeld et al., 1999) consisted of athletes completing a six-week preseason jump training program. The jump-training program was comprised of three two-week phases. The first phase was the technique phase, and consisted of athletes practicing jumping and landing mechanics using good form. The second phase, the fundamental phase, focused on building a foundation of strength, power, and agility. The third phase was the performance phase, and it focused on improving maximum vertical jump height. This jump-training program successfully reduced the number of knee injuries in a group of trained female athletes (n=366) compared to an untrained group (n=463) (Hewett, Lindenfeld et al., 1999). More specifically, untrained female athletes were 2.4 times more likely to suffer a knee injury compared to the trained female athletes. However, the results of this study were limited due to the lack of randomization, blinding, and low number of observed injuries.

The program developed by Mykelbust et al. (Myklebust, Engebretsen et al., 2003) consisted of a five-phase program performed on three different surfaces (floor, mats, and wobble boards). This program primarily focused on neuromuscular control during static and dynamic skills (e.g., single leg balance, planting, and landing skills). The program was implemented as a 15-20 minute warm-up during a 5-7 week preseason, and once a week during the actual season. The initial study analyzed the effects of this program on the incidence of ACL injury in female handball players. The results demonstrated a statistically significant decrease in the incidence in noncontact ACL injuries only for handball players in the elite division who were compliant with the program. More recently, Olsen et al. (Olsen, Myklebust et al., 2005) analyzed the preventative effects of a program similar to that of Mykelbust et al. (Myklebust, Engebretsen et al., 2003). Their program consisted of a warm-up, technique, balance, and strength and power phases. The program was implemented for the first 15 consecutive training sessions, and then once per week throughout the season. Results indicated an 80% reduction in the number of knee ligament injuries in the intervention group compared to the control group.

The prevention program developed by Mandelbaum et al. (Mandelbaum, Silvers et al., 2005), known formally as the Prevent Injury and Enhance Performance (PEP) program, was a 20-minute warm-up specifically designed for soccer. In the initial study, Mandelbaum et al. had female soccer players (ages 14-18) perform the program prior to practice and games throughout the season. Results demonstrated a 74-88% reduction in ACL injuries for trained participants

compared to untrained participants. However, results of the study were limited due to lack of randomization of the study's participants, which could have led to Hawthorne effects and selection and motivational biases. More recently, Gilchrist et al. (Gilchrist, Mandelbaum et al., 2008) implemented the PEP program in Division I women's soccer. This randomized-controlled trial consisted of 1435 athletes (853 control; and 583 intervention). Athletes in the intervention group performed the PEP program three times per week throughout the regular season. Results indicated that athletes in the intervention group were 3.3 less likely to suffer a noncontact ACL injury ($p=0.066$). In addition, athletes in the intervention group who had previously suffered an ACL injury were significantly ($p=0.046$) less likely to suffer another ACL injury compared to similarly matched controls.

Despite the successful reduction of knee injuries, particularly ACL injuries, some coaches might not adopt these neuromuscular training programs due to the large time commitment required by their comprehensive nature (Hewett, Shultz et al., 2007). Moreover, the high volume in training might actually increase the risk of injury, especially for populations that have an elevated injury risk (e.g., adolescent female athletes) (Hewett, Shultz et al., 2007). Therefore, further investigations are needed to evaluate the effect of each training component on altering landing, cutting, and pivoting techniques.

A recent meta-analysis of ACL injury prevention programs found that technique training was a common component of programs that were successful in reducing ACL injuries (Hewett, Ford et al., 2006). These programs have

typically provided feedback to the athlete about their overall trunk and lower extremity alignment. In Hewett et al. (Hewett, Stroupe et al., 1996; Hewett, Lindenfeld et al., 1999), a trainer provided verbal cues to high school volleyball, basketball, and soccer players during each session of training on various tasks involving jumping-landings. Myklebust et al. (Myklebust, Engebretsen et al., 2003) used a dyad training procedure in which participants received feedback from a training partner. In this study, female netball athletes and their training partners coached each other on proper knee alignment (i.e., avoiding excessive knee valgus). Mandelbaum et al. (Mandelbaum, Silvers et al., 2005) used a modeling protocol in which adolescent female soccer players viewed a training video that demonstrated female members of the US Olympic Development program performing each component of the program. For each exercise, models presented both correct and incorrect technique. An emphasis was placed on increasing hip and knee flexion during jump-landings with a goal of reducing forces on the lower extremities.

Technique Training Studies: An assessment of methodology related to known principles of motor skill instruction

Although no studies have examined the effects of technique training alone on the reduction of knee injuries, there is evidence that technique training can alter participants' jump-landing styles in ways that are currently thought to reduce the risk of knee injury. However, the long-term effect of technique training is debatable since most jump-training studies assessed only the temporary motor performance effects following a short period of instruction and/or practice. The

overall effectiveness of technique training should be determined by its ability to create permanent changes (i.e., motor learning) in jump-landing styles.

Therefore, a retention test should be included in future studies to determine whether technique training has resulted in motor learning (Schmidt and Lee, 2005). A retention test consists of having participants repeat the motor skill under identical conditions after a period of no practice (i.e., retention interval). This retention interval allows for any temporary performance effects to subside. As a result, any changes that are maintained following a retention interval most likely occurred as a result of motor learning.

Technique training studies have primarily used verbal instructions, demonstrations, or feedback, either in isolation or in some combination with each other, in efforts to alter lower extremity motion patterns during jump-landings. The following section focused on motor behavior literature related to the effects of instructions, demonstrations, and feedback on motor skill performance and learning. The experimental procedures of technique training studies were also reviewed to determine how well grounded their procedures were in terms of known principles of motor skill instruction.

Preparing the Stage for Motor Learning

Prior to actual physical practice of any motor skill, teachers must take the necessary steps to provide an environment to promote motor learning. First, teachers must provide motivation for the learning of the movement skill (Schmidt and Lee, 2005; Rose and Christina, 2006). This can be accomplished by educating participants about the importance of learning the new skill (Schmidt

and Lee, 2005). For example, participants of ACL injury prevention programs could be informed about the potential benefits of jump training programs (e.g., performance enhancements (Hewett, Stroupe et al., 1996) and reduction of knee injury (Hewett, Lindenfeld et al., 1999; Myklebust, Engebretsen et al., 2003; Mandelbaum, Silvers et al., 2005)). Once the learner is motivated, teachers must effectively introduce and explain the motor skill (Schmidt and Lee, 2005; Rose and Christina, 2006). Frequently, these introductions and explanations are provided to learners through instructions and demonstrations.

Instructions

Instructions can be helpful in providing the learner with an idea of the movement or skill, thus serving as a means of guiding the learner prior to their first attempt. Instructions are typically provided in verbal form, but may also be written (Schmidt and Wrisberg, 2008). Motor behavior experts recommend that instructions be kept simple and reflect only the most global aspects of the movement (Schmidt and Lee, 2005). Teachers must be aware that too much information may overload the learner and could degrade or impede motor skill performance and learning (Schmidt and Lee, 2005). Therefore, experts suggest that only one or two of the key elements associated with the skill be delivered to the learner during the acquisition phase (i.e., practice) (Schmidt and Lee, 2005).

Several technique training studies have provided participants with verbal instructions prior to practice (Gervais, 1997; McNair and Prapavessis, 1999; McNair, Prapavessis et al., 2000; Onate, Guskiewicz et al., 2001; Cowling, Steele et al., 2003; Prapavessis, McNair et al., 2003; Onate, Guskiewicz et al.,

2005; Cronin, Bressel et al., 2008; Mizner, Kawaguchi et al., 2008). Prapavessis and McNair (Prapavessis and McNair, 1999), McNair et al. (McNair, Prapavessis et al., 2000), and Prapavessis et al. (Prapavessis, McNair et al., 2003) have tested the effects of verbal instruction in isolation. In these studies, participants were instructed “to land on the balls of their feet with bent knees and upon landing lower their heels slowly to the ground while bending their knee well after landing”. In addition, Prapavessis et al. (Prapavessis, McNair et al., 2003) instructed participants to use the sound of their landing to tell them how softly they have landed. The outcomes of these studies indicated that their instructions resulted in temporary reductions in vertical ground reaction force peaks during the jump-landing. However, Prapavessis and McNair (Prapavessis and McNair, 1999) and McNair et al. (McNair, Prapavessis et al., 2000) did not include a retention test, so it was not known whether their instructions would have resulted in permanent changes (i.e., motor learning). In contrast to the other two studies, Prapavessis et al. (Prapavessis, McNair et al., 2003) did include a retention test. Unfortunately, their instructions did not result in permanent reductions in ground reaction forces after a 3-month retention interval. They noted that only 47% of their participants were able to recall at least three of the five salient points of the instructions at the 3-month retention test. This finding emphasizes the importance of keeping verbal instructions simple and precise.

Instructors must also consider where they direct the learner’s attentional focus when providing them with verbal cues. Researchers have typically classified the direction of a learner’s attention focus as either external or internal

(Schmidt and Wrisberg, 2008). An external focus directs the learner's attention on "attending to the consequences of the action to be produced", while an internal focus directs the learner's attention "to the movement of the body that actually make the action". Several studies have suggested that an external focus results in better motor skill performance and learning compared to an internal focus (Wulf, McNevin et al., 2001; McNevin, Shea et al., 2003; Wulf, Weigelt et al., 2003; Wulf and Su, 2007). Researchers have explained the positive benefits of an external focus with the constrained action hypothesis (Wulf, McNevin et al., 2001; McNevin, Shea et al., 2003). In short, it is hypothesized that an external focus allows a learner to rely more on automatic motor processes by avoiding the motor system constraint that is created by an internal focus.

McNair et al. (McNair, Prapavessis et al., 2000) assessed the effects of an external and internal attentional focus aim at altering jump-landing mechanics. In their study, participants were provided with either a technical instruction focusing on the movements of the knee and ankles (i.e., an internal focus) or an auditory cue directing participants to focus on the sound associated with the jump-landing (i.e., external focus). Results suggested that both foci resulted in improved performance (i.e., decrease in ground reaction forces). McNair et al. (McNair, Prapavessis et al., 2000) did not include a retention test, so it remains unknown if an external focus would have resulted in superior motor learning. In a previously mentioned study, Prapavessis et al. (Prapavessis, McNair et al., 2003) provided participants with instructions that directed the participants to both internal and external foci. The results of the study demonstrated that their instructions

resulted in temporary reductions in vertical ground reaction forces immediately following several practice sessions. However, participants were unable to maintain these reductions in vertical ground reaction forces following a 3-month retention interval. They concluded that their verbal instructions resulted in only temporary performance effects and not motor learning. It is quite possible that these instructions could have overloaded the attentional capacities of the learner as previously mentioned. The instructions might have also resulted in increased complexity by directing participants' attention to both external and internal foci, which could have impeded motor learning.

Demonstrations

Demonstrations (i.e., models) are frequently used by teachers to provide learners with a visual representation of a movement skill prior to physical practice. Learners usually observe another individual model the skill prior to their attempt at performing the task (Rose and Christina, 2006). Demonstrations are typically provided in a short amount of time (Rose and Christina, 2006). Therefore, the relative short duration of demonstrations may be advantageous compared to lengthy verbal instructions.

Model types are typically defined as either a correct or learning model (McCullagh and Weiss, 2002). A correct model consists of a skilled performer demonstrating the skill flawlessly, while a learning model is demonstrated by an unskilled performer. Early motor behavior research indicated that a learning model was more effective than a correct model during the learning of a simple timing task, but only when the learner was provided feedback about the model's

outcome (McCullagh and Caird, 1990). In a later study, McCullagh and Meyer (McCullagh and Meyer, 1997) found that correct and learning models were equally as effective when feedback about the model was provided to the learner. In another study, Herbert and Landin (Hebert and Landin, 1994) found that participants who were provided feedback about a learning model along with feedback about the learner's performance demonstrated the most motor learning. The results of these studies suggested that motor learning was facilitated when feedback about the model's outcome and feedback about the learner's performance were provided.

Several of the technique training studies used modeling as a means of providing information to participants prior to physical practice (Onate, Guskiewicz et al., 2005; Cronin, Bressel et al., 2008; Mizner, Kawaguchi et al., 2008). Demonstrations of jump-landings were presented to participants either by a coach (Cronin, Bressel et al., 2008), clinician (Mizner, Kawaguchi et al., 2008), or through the use video (Onate, Guskiewicz et al., 2005). Cronin et al. (Cronin, Bressel et al., 2008) provided participants with a correct model prior to jump-landing practice, while Mizner et al. (Mizner, Kawaguchi et al., 2008) provided their participants with a learning model followed immediately by a correct model prior to training. Cronin et al. (Cronin, Bressel et al., 2008) and Mizner et al. (Mizner, Kawaguchi et al., 2008) also provided participants with verbal feedback about their landing mechanics during the practice of jump-landings. In another study, Onate et al. (Onate, Guskiewicz et al., 2005) showed participants a video of a correct model and also provided them with feedback about the model's

performance. In addition, Onate et al. (Onate, Guskiewicz et al., 2005) provided a group of participants with video replays of their jump-landings in addition to the video of a correct model. The results of all three studies demonstrated improved motor skill performance of jump-landings. Moreover, Onate et al. (Onate, Guskiewicz et al., 2005) demonstrated that the use of a correct model resulted in motor learning following a one-week retention interval, but only when additional augmented feedback was provided to the participant. The results of these studies provide support for the inclusion of demonstrations in jump-training instruction. Moreover, the importance of providing learners with feedback, whether specific to the model and/or to their performance, is also evident.

Feedback

Most motor behavior experts agree that feedback is the single most important variable for motor learning with the exception of practice (Schmidt and Lee, 2005). Feedback is information that occurs as a result of performance and is typically classified as either inherent feedback or augmented feedback (Rose and Christina, 2006). Inherent feedback occurs as a natural result of the movement and is provided by one's sensory mechanisms, such as vision, audition, and somatosensation. Conversely, augmented feedback is provided by an external source and is complementary of the already present inherent feedback (Rose and Christina, 2006).

Several of the technique training studies analyzed the effects of using inherent feedback as a means of altering their jump-landing patterns (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000; Onate,

Guskiewicz et al., 2001). These studies instructed participants to use available sensory information from baseline trials in efforts to decrease vertical ground reaction forces (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000; Onate, Guskiewicz et al., 2001). Their results indicated that the use of inherent feedback alone was inferior to other interventions, such as verbal instructions (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000) and videotape feedback (Onate, Guskiewicz et al., 2001), in terms of improving motor performance. Based on these findings, participants in jump-training programs may have difficulty in understanding how to best use their available inherent feedback during training. Therefore, participants may benefit from having their attention focused on movement-related effects, such as the sound of their landing, to more effectively use their available inherent feedback.

Augmented feedback can serve several functions that promote motor learning. For example, augmented feedback can act to provide the learner with information regarding their performance (Rose and Christina, 2006; Schmidt and Wrisberg, 2008). Information about errors provides learners with a basis for developing their own error-detection and error-correction capabilities.

Augmented feedback can also serve as motivation (Rose and Christina, 2006; Schmidt and Wrisberg, 2008). This motivation may result in increased practice and indirectly facilitate motor learning. In addition, feedback can serve as positive or negative reinforcement (Rose and Christina, 2006; Schmidt and Wrisberg, 2008). In the case of positive reinforcement, the feedback attempts to increase the chances of similar subsequent performances. Conversely,

augmented feedback can serve as a negative reinforcement when the removal of certain aspects of the performance is the desired outcome. Augmented feedback may also result in a dependency-producing property (Schmidt and Wrisberg, 2008). Although this dependency typically results in good motor performance when feedback is present, the removal of feedback can quickly result in decreased performance. Fortunately, this negative “guidance” effect can be minimized by reducing the frequency of the feedback provided to the learner throughout the training phase. Recent evidence has suggested that learners should be allowed to self-control the scheduling of the feedback provided by the instructor in order to minimize this dependence property (Janelle, Kim et al., 1995; Chiviacowsky and Wulf, 2005).

Augmented feedback (e.g., verbal and videotape feedback) provides additional information to the learner above and beyond the already present inherent feedback and may facilitate the learning of a motor skill. Augmented feedback is typically categorized as either knowledge of performance (KP) or knowledge of results (KR) (Schmidt and Wrisberg, 2008). KP is augmented information that is provided to the individual about the quality of their movement during a particular motor skill, while KR is augmented information provided to the individual about whether or not the desired movement outcome was met. KP typically provides the learner with additional information regarding their performance, while KR is typically seen as being redundant. However, KR may be useful if learners are unaware of the desired result and have difficulty interpreting their inherent feedback (Schmidt and Wrisberg, 2008). Several of

the jump-training studies (Onate, Guskiewicz et al., 2001; Onate, Guskiewicz et al., 2005; Cronin, Bressel et al., 2008; Mizner, Kawaguchi et al., 2008) provided KP to participants, while no study provided participants with KR. Therefore, the potential benefits of providing KR to participants in jump-training programs is unknown.

Cronin et al. (Cronin, Bressel et al., 2008) and Mizner et al. (Mizner, Kawaguchi et al., 2008) provided participants of their technique training studies with augmented feedback through verbal cues aimed at altering their jump-landing mechanics. Both studies also provided participants with verbal instructions and demonstrations prior to physical practice. Their results demonstrated that their jump-training procedures resulted in temporary improvements in jump-landing mechanics. However, it is unknown what role verbal feedback played in these temporary performance effects due to the multiple instructional components (i.e., instruction, demonstration, and feedback) used in these studies.

Videotape replay of jump-landings was another form of augmented feedback used in technique training studies (Onate, Guskiewicz et al., 2001; Onate, Guskiewicz et al., 2005). Motor behavior research has indicated that learners must be provided with additional cues aimed at directing the learner's attention to specific aspects of the video replay in order to optimize learning (Kernodle and Carlton, 1992). Onate et al. (Onate, Guskiewicz et al., 2001; Onate, Guskiewicz et al., 2005) implemented this recommendation in both of their technique training studies. In their studies, participants were provided with

videotape replays of their jump-landings during baseline testing. Additionally, a clinician provided learners with verbal cues regarding specific elements of the jump-landing during the viewing of the video replay. Results of both studies suggested that the use of videotape feedback was an effective means of providing motor skill instruction for the learning of jump-landings. However, in both studies, videotape feedback was provided only within a single session. Rose and Christina (Rose and Christina, 2006) suggested that learners need sufficient time to view videotape feedback in order to gain the most benefits of this form of feedback. Experts have suggested that learners be provided with videotape feedback for a minimum of five weeks for optimal performance effects (Rose and Christina, 2006).

Strengths

Over the past 10 years, a large amount of research has been performed analyzing the effects of jump-landing training procedures (i.e., instruction, demonstrations, and feedback) on motor skill performance and learning. Researchers have demonstrated that verbal instructions can result in temporary learning effects (i.e., decreased ground reaction forces). Technical instructions have focused participants on increasing the amount of flexion of the knees and ankles, while other verbal instructions have focused participants on decreasing the sound of subsequent landings. Jump-landing training procedures have also successfully incorporated demonstrations by providing participants with feedback about the model's performance. Moreover, augmented feedback has been found to enhance motor skill performance and learning by providing participants with

information about the quality of their movement. Videotape feedback was found to be an effective means of providing augmented feedback, especially when the learner was directed to key elements of the jump-landing.

Limitations

Despite the numerous strengths of the technique training studies, several limitations were identified. The most significant shortcoming was that most studies did not include a long-term retention test. Therefore, most studies were limited to providing only evidence of temporary learning effects. Technique training procedures also tended to provide participants with a large amount of information regarding jump-landing mechanics during a relatively short training session. While these procedures resulted in temporary learning effects, the potential for information overload could negate any potential long-term motor learning effects. Moreover, the use of multiple instructional components (i.e., instructions, demonstrations, and feedback) made it impossible to determine which instructional component(s) led to the improvements. It is quite possible that some of the information provided by each instructional component may overlap, thus resulting in redundant information and a less efficient jump-training program.

Future Research

Future research should focus on developing efficient and effective jump training procedures that are based on sound principles of motor skill instruction. First and foremost, researchers must include retention testing in their experimental designs to determine whether or not their jump-landing training

procedures result in motor learning. Verbal instructions should be kept simple and precise to avoid informational overload. Moreover, researchers should attempt to develop verbal instructions that direct the learner's attention to an external focus. For example, jump-training programs could use a mirror to provide the athlete with an external focus (i.e., the image in the mirror) during the practice of jump-landings. Verbal instructions related to the image's lower extremity alignment could be provided to the participant in efforts to alter their jump-landings in ways that are currently thought to reduce the risk of knee injury (e.g., avoiding excessive knee valgus).

Research designs that involved multiple instructional components must consider the potential individual contributions that each component may have on jump-landing performance and learning. Initially, researchers could perform exit interviews of participants in efforts to identify the primary training component(s) used by participants during motor skill instruction. This information may help in developing more effective and efficient jump-landing training procedures that could be tested in subsequent studies. Finally, future research should assess whether their jump-landing training procedures result in similar alterations in lower extremity movement patterns during other high-risk sport-specific tasks. If these alterations in movement patterns do transfer over to similar jump-landing skills (e.g., stop-jump task), then preventative programs could be made more efficient by removing tasks that are similar in technique.

Research investigations into technique training will ultimately provide researchers, clinicians, and coaches with much needed answers regarding the

role that technique training plays in reducing knee injuries. Further research into technique training will hopefully result in more efficient and effective jump-training programs, so that coaches and trainers are more likely to implement these programs both on the field and in the clinic.

Biomechanical Rationale for Kinetic Outcome Measures

Several studies have assessed the effects of technique training on altering jump-landing techniques. The majority of these studies assessed the peak vertical ground reaction forces of the jump landing to determine the success of their jump-landing training procedures (Gervais, 1997; Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000; Onate, Guskiewicz et al., 2001; Cowling, Steele et al., 2003; Prapavessis, McNair et al., 2003; Onate, Guskiewicz et al., 2005; Cronin, Bressel et al., 2008; Mizner, Kawaguchi et al., 2008). In these studies, a significant decrease in vertical ground reaction forces was the desired outcome. Onate et al. (Onate, Guskiewicz et al., 2005) and Mizner et al. (Mizner, Kawaguchi et al., 2008) were the only investigators that measured joint kinetics to assess for potential reductions in knee joint loading and, indirectly, ACL loading. Specifically, Onate et al. (Onate, Guskiewicz et al., 2005) assessed peak proximal anterior tibial shear forces, while Mizner et al. (Mizner, Kawaguchi et al., 2008) analyzed sagittal and frontal plane knee moments. Future technique training studies should analyze key biomechanical variables that have been shown to directly or indirectly affect the loading of the ACL. A significant decrease in outcome measures associated with ACL loading would provide

stronger evidence that the jump-landing training procedures may have the potential to prevent ACL injury.

Therefore, the purpose of the following section was to provide a biomechanical rationale for each primary kinetic variable that I plan to include in my dissertation. An additional purpose was to provide evidence that each primary variable will be useful in discriminating between high risk and low risk landing styles. The primary kinetic variables that I plan to include in my dissertation are peak internal knee adduction moment, peak internal knee extension moment, and peak vertical ground reaction force during the landing phase of a countermovement jump and stop-jump task.

Peak Internal Knee Adduction Moment

Several studies have investigated the mechanisms of ACL injuries in various sports through retrospective interviews (Boden, Dean et al., 2000; Olsen, Myklebust et al., 2004) and qualitative video analyses (Boden, Dean et al., 2000; Olsen, Myklebust et al., 2004). Olsen et al. (Olsen, Myklebust et al., 2004) found that the majority of mechanisms in their study of handball players were the result of a plant-and-cut movement. Video analyses observed that this plant-and-cut movement was associated with a forceful valgus of the knee. Olsen et al. (Olsen, Myklebust et al., 2004) also noted that a forceful valgus motion was associated with single-legged jump landing, which was another common mechanism of injury. In another qualitative video analysis of 39 ACL injuries, researchers found that females were five times more likely to suffer a valgus

collapse compared to males. Based on these studies, valgus loading of the knee appears to be directly associated with ACL injuries.

Biomechanical research aimed at determining the strain and forces in the ACL under combined knee loading has also provided further support for including peak internal knee adduction moment as a primary variable. Berns et al. (Berns, Hull et al., 1992) assessed the strain of the anteromedial bundle of the ACL of 13 knee cadavers under pure and combined loads. Their results demonstrated that a pure valgus torque did not result in a significant strain of the ACL. However, combination loading consisting of an anterior force and valgus torque did result in a significant increase in ACL strain. Markolf et al. (Markolf, Burchfield et al., 1995) provided additional data about the effects of combined knee loading on ACL forces. In their study, the effects of pure and combination loading were assessed on 14 knee cadavers. Their results suggested that a pure valgus torque did result in significant increase in ACL force at knee angles greater than 5°. In addition, valgus torque resulted in additional forces to the ACL when applied to an already present anterior tibial force. Markolf et al. (Markolf, Burchfield et al., 1995) concluded that the ACL was at risk for injury when undergoing an anterior tibial force in combination with a valgus torque.

A recent cadaveric study assessed the strain properties of the ACL during a simulated one-legged jump landing with and without the addition of an external valgus moment (Withrow, Huston et al., 2006). Knee specimens were initially placed in 25° of flexion to simulate the position of the knee at initial contact during a jump landing. The knees were allowed to move in all degrees of freedom.

Additionally, the quadriceps, hamstrings, and gastrocnemius tendons were pre-tensioned to simulate muscle co-activation prior to landing. Aircraft cables were also attached to these tendons during the simulated landing to replicate the dynamic resistance of these muscles. A 150-N weight was placed in series with the proximal femur and was released to create a compressive force and flexion moment about the knee joint. They found that the additional valgus moment resulted in a 30% increase in ACL strain. This finding suggested that the presence of an external valgus moment during a jump landing was associated with increases in strain of the ACL. A recent computer model also arrived at similar conclusions (Shin, Chaudhari et al., 2009). In this study, researchers validated their three-dimensional dynamic specimen-specific force-driven knee model using the methods developed by Withrow et al. (Withrow, Huston et al., 2006). Their findings also demonstrated that peak ACL strain was increased by 30% when maximum valgus moments were applied to the model.

Several biomechanical studies have also found significant differences in frontal plane kinematics and kinetics during a variety of tasks, including running (Malinzak, Colby et al., 2001), shuttle run (McLean, Walker et al., 2005), side-step (Malinzak, Colby et al., 2001; McLean, Walker et al., 2005), cutting (Malinzak, Colby et al., 2001; Ford, Myer et al., 2005; McLean, Walker et al., 2005), stop-jump tasks (Chappell, Yu et al., 2002; Ford, Myer et al., 2005), double-leg (Ford, Myer et al., 2003; Kernozek, Torry et al., 2005), and single-leg drop jump landings (Ford, Myer et al., 2006; Pappas, Hagins et al., 2007). These studies determined that females were in a position of greater valgus at initial contact

(McLean, Walker et al., 2005) and demonstrated greater peak valgus angles (Ford, Myer et al., 2003; Ford, Myer et al., 2005; Kernozek, Torry et al., 2005; McLean, Walker et al., 2005; Ford, Myer et al., 2006; Pappas, Hagins et al., 2007) during the stance or landing phase of the task. Malinzak et al. (Malinzak, Colby et al., 2001) found that females positioned their knee in more valgus (approximately 11 degrees) throughout the entire stance for running and side-step and cutting tasks. In addition, Chappell et al. (Chappell, Yu et al., 2002) found greater peak external valgus moments during the landing phase of a stop-jump task. Altogether, these studies provide additional evidence that excessive valgus loading in the frontal plane may play a role in noncontact ACL injuries.

A recent prospective study by Hewett et al. (Hewett, Myer et al., 2005) has provided the strongest evidence that peak internal knee adduction moment should be included as a primary variable. In this study, a cohort of 205 female adolescent soccer, basketball, and volleyball players were followed for a period of one to two seasons (i.e., two fall seasons and one winter season). Prior to injury surveillance, kinematic and kinetic baseline measures were collected during a drop vertical jump. Logistic regression analysis indicated that peak knee abduction moment was a significant predictor of ACL injury. Furthermore, external knee abduction moment had a sensitivity of 73% and a specificity of 78% for predicting ACL injury. An ANOVA also indicated a significant difference in peak external abduction moments (45.3 Nm vs. 18.4 Nm) between females who suffered an injury vs. those who did not. Researchers concluded that females who experience high abduction loading are at risk of ACL injury.

Peak Internal Knee Extension Moment

Retrospective interviews and qualitative video analyses have found that ACL injuries typically occurred with the knee in a relatively extended position (Boden, Dean et al., 2000; Olsen, Myklebust et al., 2004). Therefore, an argument could be made that anterior tibial shear forces play an important factor in noncontact ACL injuries. Based on this argument, researchers have attempted to model proximal tibia anterior tibial shear forces, associated with stop-jump landings, in efforts to identify other key biomechanical variables (Yu, Lin et al., 2006; Sell, Ferris et al., 2007). The results of these two studies both demonstrated that peak internal knee extension moments are strongly correlated to peak proximal anterior shear forces. Hence, estimates of peak internal knee extension moments may be a useful variable to demonstrate the effectiveness of a jump landing training program.

Studies assessing gender differences have also provided support for including internal knee extension moment as a primary variable. Chappell et al. (Chappell, Yu et al., 2002) demonstrated significantly larger peak internal knee extension moments compared to males during a vertical stop-jump tasks. Furthermore, the peak proximal tibia anterior shear forces encountered by both females and males during the landing phase of the stop-jump task were significantly larger compared to those produced during the jumping phase. Chappell et al. (Chappell, Yu et al., 2002) concluded that the landing phase of the stop-jump task was the most stressful in terms of ACL stresses, regardless of gender. Yu et al. (Yu, Lin et al., 2006) also found similar gender differences in

peak internal knee extension moments and proximal tibial anterior shear forces during a vertical stop-jump task. These gender differences in peak internal knee extension moments and proximal anterior tibial shear forces during stop-jump tasks provide support for their usefulness in discriminating between high-risk and low-risk landing styles.

Peak Vertical Ground Reaction Force

McNair and Marshall (McNair and Marshall, 1994) found that vertical ground reaction forces and tibial accelerations associated with jump landings were positively correlated. Therefore, they suggested that a reduction in impact loads (i.e., ground reaction forces) during the landing of a jump might result in an overall decrease in knee loading. Mizner et al. (Mizner, Kawaguchi et al., 2008) provided evidence to support this theory in a study assessing the effects an jump-training procedures aimed at improving jump-landing technique (i.e., softer landings and minimal knee valgus). In this study, their technique training resulted in a 22% decrease in external abduction moments along with a similar 20% reduction in vertical ground reaction forces. However, Onate et al. (Onate, Guskiewicz et al., 2005) did not find a significant decrease in peak proximal anterior tibial shear forces, despite a significant reduction in vertical ground reaction forces. Based on these two inconclusive studies, a significant reduction in vertical ground reaction forces may or may not result in a significant decrease in knee joint loading, but is worthy of further investigation.

Further evidence to support the inclusion of peak vertical ground reaction force as a primary variable comes from biomechanical studies assessing gender

differences. Kernozek et al. (Kernozek, Torry et al., 2005) found that females exhibited greater peak vertical ground reaction forces compared to males during drop landings. In this study, females demonstrated an average peak vertical ground reaction force of 4.7 times body mass compared to 3.5 times body mass for males. Similarly, Yu et al. (Yu, Lin et al., 2006) reported a significant gender difference in peak vertical ground reaction forces during for the landing phase of a stop-jump task. In this study, female participants demonstrated an average peak vertical ground reaction force of 2.67 times body weight compared to 2.16 times body weight for males. Yu et al. (Yu, Lin et al., 2006) also found that peak vertical ground reaction force was significantly correlated with peak proximal anterior shear force ($r = 0.51$, $p < 0.001$).

Hewett et al. (Hewett, Myer et al., 2005) were the only investigators to provide evidence that peak vertical ground reaction forces may be useful in predicting individuals who are at an increased risk for suffering an ACL injury. In their study, female adolescent athletes who suffered a noncontact ACL injury landed with approximately 20% greater vertical ground reaction forces compared healthy controls. Moreover, peak vertical ground reaction forces were moderately correlated ($r=0.74$) with peak external abduction moment in those participants who suffered an ACL injury

Summary

The results of numerous biomechanical studies have demonstrated that internal extension and adduction moments of the knee most likely play a significant role in noncontact ACL injury mechanisms. The debate still remains

on whether sagittal plane loading (i.e., proximal anterior tibial shear force) plays a larger role in noncontact ACL injuries vs. frontal plane loading (i.e., valgus moment) (McLean, Andrich et al., 2005; van den Bogert and McLean, 2006). However, researchers agree that movement patterns that produce a combination of loading within the frontal and sagittal plane appear to increase risk of ACL injury (Griffin, Albohm et al., 2006). Therefore, any significant decrease in one or both of these variables most likely would result in a significant decrease in ACL loading. The reduction of vertical ground reaction forces encountered during jump landings should also help reduce the risk of ACL injury. Technique training, therefore, should attempt to alter jump-landing techniques in a manner that reduces peak internal knee extension and adduction moments and vertical peak ground reaction forces.

CHAPTER III: Materials and Methods

Participants

A total of 26 female recreational athletes who presented with medial knee displacement between 18-30 years of age were recruited from the student population of the University of Tennessee and the greater Knoxville metropolitan area by use of flyers and word of mouth. A recreational athlete was defined as a person who currently participated in a sport involving jumping (e.g., basketball, soccer, and volleyball) and previously participated in a sport involving jumping at a high school varsity level. Participants had to be physically active for a minimum of two times per week for at least 30 minutes, and had to participate in a physical activity involving jumping at least once a month. Prior to participating in this study, participants provided written informed consent (Appendices A and B). The study's procedures were approved by the University's Institutional Review Board.

Participants were excluded if they had a history of ACL injury, lower extremity fracture or surgery, lower extremity injury in the past six months which limited activity levels for more than two weeks, or previously participated in an ACL injury prevention program (Appendix C). Participants also filled out a physical activity readiness questionnaire (Appendix D) (Mahler, Froelicher et al., 1995). Any participant who answered "NO" to any of the seven questions was excluded. Participants who were considered obese based on their body mass index (i.e., > 30) (Behn and Ur, 2006) were also excluded. Participants who met the inclusion criteria and signed the informed consent were screened to

determine whether they exhibited medial knee displacement (i.e., knock-kneed position) in either or both limbs during the landing phase following a countermovement jump basketball rebound task.

A regression equation developed for a two-way mixed-model ANOVA was used to determine sample size (Park and Schutz, 1999). In this equation, the effect size was set at 0.80 and the mean correlation among repeated measure levels was set at 0.80 (Ford, Myer et al., 2007). We selected our effect size based on findings of a prospective study that indicated a large effect (effect size = 1.2) for peak knee adduction moment differences between athletes predicted to be at low and high risk for ACL injuries (Hewett, Myer et al., 2005). Therefore, an effect size of 0.8 should be a realistic reflection of magnitude of change that would be expected to reduce injury risk. Results of the power analysis indicated that 13 subjects per group would be needed to provide power at the 0.80 level for each of the primary variables (i.e., peak internal knee extension and adduction moments, peak knee abduction angle, knee excursion, and peak vertical ground reaction force).

Screening and Maximum Vertical Jump Testing

All data collection took place in the Biomechanics/Sports Medicine Laboratory. Participants wore athletic clothing during the screening, consisting of shorts, t-shirt, and tennis shoes. Participants were measured for height and weight using a standard clinical scale. Participants then performed a five-minute warm up on an exercise bike at a moderate intensity. Cycling intensity was determined using a rate of perceived exertion scale (Mahler, Froelicher et al.,

1995). After the bicycle warm-up, participants performed self-guided stretching of the quadriceps, hamstrings, and calf musculature to minimize injury risk.

Following the warm-up, participants' maximum vertical jump height for a countermovement jump was assessed using a Vertec jump height measurement device (Sports Imports Inc., Columbus, OH). Participants first stood erect with heels lifted and their dominant upper extremity extended as high as possible. This height was measured and recorded by the primary investigator. Participants were then given two practice jumps to become accustomed to the Vertec jump measurement system. During the vertical countermovement jumps, participants were allowed to bend their knees and swing their arms, but they were not allowed to take any steps. Participants were instructed to touch the Vertec vanes with their dominant upper extremity. The height of each jump was determined by subtracting the standing height with dominant arm extended from the overall jump height measured by the Vertec jump measurement system. The maximum value of the three jumps was recorded as their vertical jump height.

To determine whether participants met the medial knee displacement criterion, a two-dimensional video analysis of three acceptable countermovement jumps was conducted. Previous researchers have demonstrated a similar screening method for medial knee displacement as having acceptable intrarater and interrater agreement (Ekegren, Miller et al., 2009). The screening task was performed using the same jump technique used during the maximum vertical height assessment. Target jump height was normalized for the task by having participants grab a basketball positioned at 80% of their maximum jump height

based on the mid-line location of the basketball. The basketball was part of a jump-training device, “Exploder The System” (Innovative Fitness Products, Fayetteville, Arkansas) (Appendix E), and was tethered to a retractable cord. Participants were instructed to pull the ball down to chest level with both hands during the landing. The countermovement jump was videotaped using a JVC 6R-DVL9800 digital video camera (Victor Company of Japan, Wayne, NJ) that provided a frontal plane view of the jump-landing. The camera-to-subject distance was 5 meters to minimize perspective error (Payton and Bartlett, 2008). The optical axis of the video camera was aligned perpendicular to the frontal plane. The height of the camera was set at the level of the knees for each participant. The camera was manually focused on each participant’s knees in the plane of motion prior to taping. The digital video was directly transferred to a computer via a Firewire cable and viewed using Ariel Performance Analysis System software (Ariel Dynamics Inc., Trabuco Canyon, CA). The primary investigator determined the presence of medial knee displacement in either limb during the landing phase of the countermovement jump in all three trials. Trials in which the participant landed off-balance or off-plane, as determined subjectively by the primary investigator, were discarded. The landing phase began when the participant’s feet contacted the ground and ended at maximum frontal plane knee displacement. Medial knee displacement was defined as the midpoint of the patella passing medial to the big toe (Bell, Padua et al., 2008). Participants who did not exhibit medial knee displacement in all three trials were excluded from the training aspect of the study and their participation ended at

this point. Participants who exhibited medial knee displacement were placed randomly in one of two groups: mirror feedback group (n=13) or a no-treatment control group (n=13). Randomization for group placement was performed using a random number generator.

Equipment

Lower extremity position data were collected at 240 Hz using a seven-camera motion capture system (Vicon Oxford Metrics, Oxford, UK). Two AMTI force plates (AMTI Inc., Watertown, MA) synchronized with the motion capture system were used to collect ground reaction force data at 1200 Hz. Participants wore athletic clothing during motion analysis testing consisting of spandex shorts, sports bra, and running sandals (Bite Footwear, Redmond, WA). Reflective markers were placed on the lower extremities and pelvis to track segment motion in three-dimensional space. The marker set consisted of tracking and anatomical markers (Appendix F). Four non-collinear reflective markers attached to molded thermoplastic shells (Cappozzo, Cappello et al., 1997; Manal, McClay et al., 2000) were placed on the pelvis, bilateral thigh, and bilateral shank segments. The pelvic tracking shell was positioned over the proximal sacral region. The shells for the thighs and shanks were placed laterally on the proximal thighs and distal shanks, respectively. Tracking markers for the feet were placed on the proximal, lateral, and medial aspects of the calcanei and posterior heels. Anatomical markers were placed on each iliac crest, greater trochanter, lateral and medial knee at the level of the lateral femoral epicondyle, lateral and medial ankle at the level of the lateral malleolus, and the first and fifth metatarsal heads.

Anatomical markers were removed following the standing calibration trial. Foot position relative to the laboratory coordinate system was standardized during the static calibration using a cardboard template. This template places the heels 0.17m apart with a toe-angle of 14° (McIlroy and Maki, 1997).

Baseline Testing Protocol

Participants' movement characteristics of two movements, a countermovement jump and stop-jump task (Appendices G and H), were determined at baseline. Participants performed these two movements while three-dimensional kinematics and force data were collected. Target jump height was again normalized for both tasks by having participants grab a basketball set at 80% of their maximum jump height. The order of the movement tasks was counterbalanced. All movement tasks were described to each participant. Participants performed the same warm-up that was used prior to the screening. Participants were given ample practice to ensure that they were comfortable with the movements. Each participant performed five acceptable trials of each task. Trials in which the participant partially contacted the force plates or changed their stride in an attempt to target the force plate, as determined subjectively by the primary investigator, were discarded.

The countermovement jump was identical to the jump technique used during the screening to determine the presence of medial knee displacement. The stop-jump task was modeled based on the procedures developed by Herman et al. (Herman, Weinhold et al., 2008). The stop-jump task consisted of a four-step approach followed by a two-footed landing onto each force plate and

a two-footed takeoff. Participants were instructed to grab the basketball after takeoff and pull it down to chest level during the landing. The jump-training device was placed adjacent to the force plates such that the basketball was centered directly above the landing area (i.e., force plates).

Jump Training Protocol

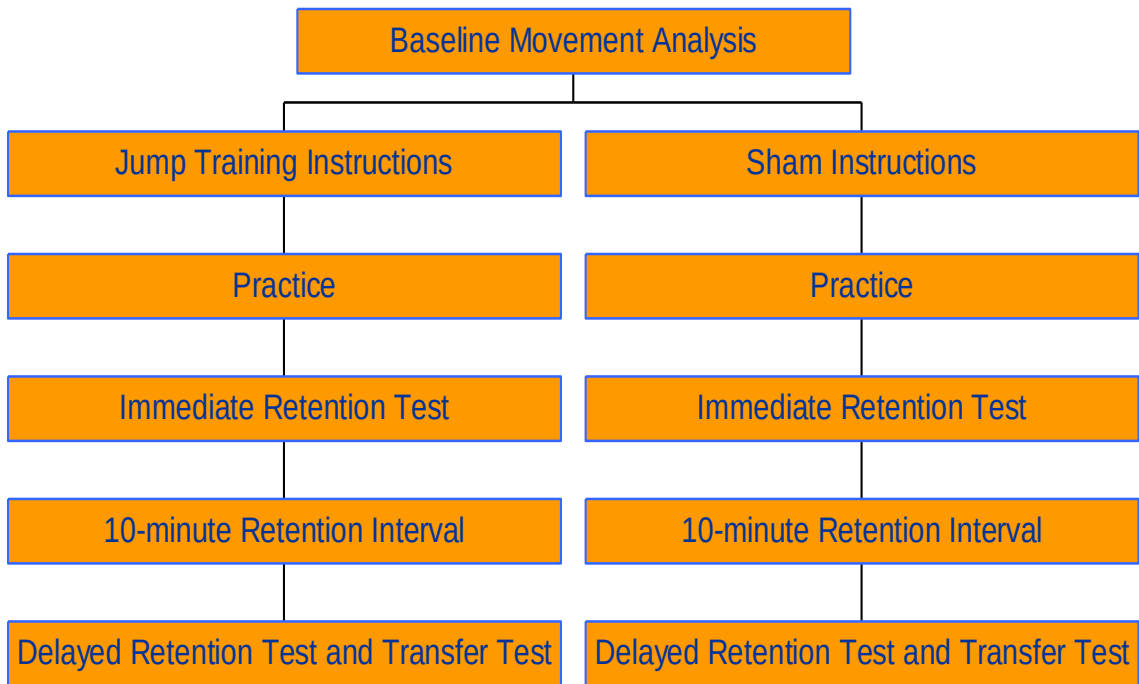
Participants in the experimental group were provided with instructions intended to decrease medial knee displacement. Participants were instructed to use their image in a mirror as an external focus. Participants performed the first practice session during phase one under the supervision of the primary investigator, and completed the other two training sessions during phase two through self-practice. Appendix I provides a diagram of the overall data collection process. Participants in the experimental group were instructed not to discuss the jump-landing instructions with other study participants or potential participants. Participants in the control group practiced countermovement jumps at a similar dosage while being instructed to jump as high as possible.

Participants were allowed to maintain their current activity levels, but were asked to refrain from beginning any new flexibility, strengthening, or aerobic activities while they were enrolled in the study. In addition, participants were instructed to avoid any strenuous activity 24 hours prior to any data collection sessions.

Phase One (Figure 1)

Immediately following baseline motion analysis testing, participants in the experimental group received the jump-landing instructions. Participants were

Figure 1. Flow-chart for Phase One.



instructed to focus on their image in the mirror, and minimize the medial knee displacement of the image by keeping the knees directly above the feet during practice jumping-landings. Next, participants practiced jump-landings using the provided instructions in front of a full-length mirror. Practice consisted of participants performing three sets of five countermovement jumps. Participants rested for 20 seconds between each jump and for two minutes between each set. Participants in the control group performed the same number of sets and repetitions of jumps while being instructed to jump as high as possible.

Following the practice session, all participants rested for five minutes. Participants then performed the immediate retention test. During this retention test, participants underwent motion analysis assessment of the countermovement jump task to assess for immediate learning effects related to the jump-training instructions. Participants performed five acceptable trials of the countermovement jump using the same protocol established during baseline testing. After the completion of the immediate retention test, all participants rested for an additional 10 minutes. During this rest period, participants were not allowed to practice jump-landings. During the delayed retention test, participants performed five acceptable trials of the countermovement jump to assess for learning effects. Participants also performed five acceptable trials of the stop-jump task to assess for any transfer effects related to the jump training instructions. The same motion capture methods that were established during baseline testing were used for both movements. The order of movement tasks was again counterbalanced.

Phase Two (Figure 2)

At the end of first data collection session, participants in the experimental group were given written and illustrated instructions of the intervention protocol to follow over the next week (Appendix J). Participants in the control group were also given written instructions to follow over the next week (Appendix K). The control group's practice schedule was based on the same dosage provided to the participants in the experimental group. Participants in both groups were required to practice countermovement jumps every other day for two additional sessions for a total of three practice sessions (first day included). For example, a participant who underwent baseline testing on Monday performed the at-home intervention on Wednesday and Friday. Subjects were instructed to perform a warm-up that consisted of walking slightly above normal pace for three to five minutes followed by stretching of the quadriceps, hamstrings, and calf musculature, prior to each practice session. Following the warm-up, participants performed a total of three sets of five countermovement jumps using the provided jump training instructions. In addition, participants in the experimental group performed their practice in front of a full-length mirror to provide feedback regarding the presence of medial knee displacement. A full-length mirror was provided to participants if needed. Based on motor learning principles (Schmidt and Lee, 2005), the frequency of the mirror feedback was faded over the second and third session. During the second practice session, participants were instructed to use the mirror for the first two sets of jumps. Participants then

Figure 2. Flow-chart of Phase Two.



performed the final set of jumps without use of the mirror. During the third practice session, participants only used the mirror for the first set of jumps.

The second data collection session occurred approximately one week following the first data collection session, exactly three days following the final practice session to assess for any learning effects related to the jump training instructions. During this first retention test of phase two, all participants performed five successful trials of the countermovement jump using the same protocol established during baseline testing. After the completion of the first retention test, participants were scheduled to return to the lab in one week, exactly 10 days following the third and final practice session. All participants were asked not to practice jump-landings during this time. During this second retention test of phase two, participants repeated the countermovement jump task to assess for learning effects related to the jump training instructions. Participants also repeated the stop-jump task to assess for any transfer effects related to the jump training instructions. The same motion capture methods that were established during baseline testing were used during the retention and transfer tests. The order of movement tasks was counterbalanced.

Data Reduction

Kinematic and kinetic data were reduced with Visual 3D (C-Motion, Rockville, MD). Three-dimensional position data were low-pass filtered at 6 Hz and ground reaction force data were low-pass filtered at 60 Hz using 4th-order Butterworth filters. Filter cut-off frequencies were determined using residual analysis developed by Winter (Winter, 1990). Residual plots for each movement

tasks for two randomly sampled participants were analyzed using Winter's methods to assist in determining the cut-off frequency. The three-dimensional coordinates of the hip joint center were estimated from the three-dimensional marker coordinates of the right and left greater trochanter markers. Hip joint centers were placed at a distance of 25% of the total distance from greater trochanter to greater trochanter. The three-dimensional coordinates of the knee joint center were determined as the mid-point between the lateral and medial femoral epicondyle markers. Similarly, the three-dimensional coordinates of the ankle joint centers were determined as the middle point between the lateral and medial malleolus markers. Joint angles were defined using the right-hand rule as three Euler angles with flexion-extension, abduction-adduction, and internal-external rotation as the first, second, and third rotation, respectively. Joint resultant force and moment data were determined using inverse dynamics and anthropometric data estimated from mass and height (Dempster, 1955), segmental kinematic data, and ground reaction force data. Joint moments were expressed as net internal joint moments and normalized to body mass (Nm/kg). Ground reaction force data were normalized to body weight. The maximum value of each dependent variable were calculated during the landing phase of the jump-landing for the countermovement jump and stop-jump tasks. All variables were determined for the limb that exhibited the greatest amount of medial knee displacement during the screening for all five trials of each task and averaged within the task. A coin flip was used to determine the side of interest in instances which the participant's exhibited similar amounts of medial knee displacement as

judged by the primary investigator. The landing phase of the countermovement jump and first landing phase of the stop-jump task was defined as the interval between the initial contact of the dominant leg onto the force plate (i.e., > 10N) and maximum knee flexion during the stance phase.

Statistical Analysis

Summary statistics were generated for subjects' age, mass, height, and jump height. Independent-samples *t*-tests were performed to assess any significant differences in age, weight, height, body mass index, and vertical jump height between groups. Effect sizes were calculated for each primary outcome variable. Effect sizes were calculated by subtracting the mean score at baseline from the mean score during each retention or transfer test, and then dividing by a pooled standard deviation of the baseline and retention and/or retention standard deviations (Cohen, 1988). Percent differences were also calculated to aid the interpretation of the results.

Phase One

Each kinematic and kinetic dependent variable for the countermovement jump was analyzed using a 2 x 3 mixed-model ANOVA for two factors: group (experimental and control) and time (baseline, immediate retention test, and delayed retention test). If the overall ANOVA test was significant, then Fisher's least significant difference (LSD) post hoc test were performed to determine where any statistically significant differences existed between the group and test conditions for statistically significant time and interaction effects. Specifically, seven paired contrasts were of interest for interaction effects and consisted of the

following: (1) experimental baseline vs. control baseline, (2) control baseline vs. control immediate retention test, (3) control immediate retention test vs. control delayed retention test, (4) control baseline vs. control delayed retention test, (5) experimental baseline vs. experimental immediate retention test, (6) experimental immediate retention test vs. experimental delayed retention test, and (7) experimental baseline vs. experimental delayed retention test. In addition, descriptive statistics (i.e., mean, standard deviations, effect size, and percent differences) for proximal and distal sagittal plane kinematic of the hip and ankle were calculated for the countermovement jump to aid in the interpretation of the results. A separate 2 x 2 mixed-model ANOVA for two factors: group (experimental and control) and time (baseline and transfer) was performed to assess for the presence of motor transfer during the stop-jump task. A Type-I error rate of 0.05 was chosen as an indication of statistical significance for all ANOVA analyses.

Phase Two

Each kinematic and kinetic dependent variable for the countermovement jump was analyzed using a 2 x 3 mixed-model ANOVA for two factors: group (experimental and control) and time (baseline, retention test one, and retention test two). If the overall ANOVA test was significant, then Fisher's least significant difference (LSD) post hoc test were performed to determine where any statistically significant differences existed between the group and test conditions for statistically significant time and interaction effects. Specifically, seven paired contrasts were of interest for interaction effects and consisted of the following:

(1) experimental baseline vs. control baseline, (2) control baseline vs. control retention test one, (3) control retention one vs. control retention two, (4) control baseline vs. control retention two, (5) experimental baseline vs. experimental retention one, (6) experimental retention one vs. experimental retention two, and (7) experimental baseline vs. experimental retention two. In addition, descriptive statistics (i.e., mean, standard deviations, effect size, and percent differences) for proximal and distal sagittal plane kinematic of the hip and ankle were calculated for the countermovement jump to aid in the interpretation of the results. A separate 2 x 2 mixed-model ANOVA for two factors: group (experimental and control) and time (baseline and transfer) was performed to assess for the presence of motor transfer during the stop-jump. A Type-I error rate of 0.05 was chosen as an indication of statistical significance for all ANOVA analyses. All ANOVA analyses were conducted using SAS 9.2 (Cary, NC).

CHAPTER IV: Results

Participants

Thirty-eight individuals from the University of Tennessee campus and Knoxville area participated in the screening. Nine participants were excluded after the screening because they did not exhibit medial knee displacement. Two participants did not participate after the screening as a result of suffering an ankle injury prior to the first laboratory visit. Another subject's data were not included due to a shoulder injury that occurred prior to her third laboratory visit. A total of twenty-six participants exhibited medial knee displacement in at least one knee and completed the study protocol. Baseline motion analysis revealed that all participants did indeed land with their knee in dynamic valgus, with peak knee abduction angles ranging from -3.7 to -17.4° . Thirteen participants were included in the experimental group and 13 participants were enrolled in the control group.

Each participant participated in one or more of the following high school varsity sports associated with ACL injury risk: basketball, volleyball, soccer, gymnastics, or ballet. In all, 69% (18/26) of participants played volleyball, 31% (8/26) played basketball, 23% (6/26) played soccer, and 15% (4/26) participated in competitive gymnastics or ballet (Table 1).

Individual values for descriptive data for all participants appear in Appendix L. The mean age for participants was 21.2 (SD=2.2) years. Average height and weight of participants were 1.66 (SD=0.07) meters (m) and 64.1 (SD=9.1) kilograms (kg). The mean body mass index was 23.1 (SD=2.1) kg/m^2 . Participants' average vertical jump height was 0.36 (SD= 0.07) m. Group mean

Table 1. Participants' history of sports.

Participant	Volleyball	Basketball	Soccer	Gymnastics Or Ballet
1	X			X
2	X			
3	X	X		
4	X			
5	X			X
6	X	X		
7			X	
9	X			
11	X			
12		X		
13		X	X	
14				X
15	X			
16	X			
17	X	X		X
18			X	
19	X			
20	X			
21	X	X		
22	X			
23	X	X		
24			X	
26		X		
27	X		X	
28	X			
29			X	
TOTAL	18	8	6	4
%	69%	31%	23%	15%

Table 2: Mean (SD) for Age, Height, Weight, BMI*, and Maximum Vertical Jump Height for Experimental and Control Groups.

	<i>Experimental</i>	<i>Control</i>
Age, yrs	21.7 (1.9)	20.6 (2.4)
Height, m	1.66 (0.08)	1.67 (0.06)
Weight, kg	62.4 (7.0)	65.7 (10.9)
BMI*, kg/m ²	22.6 (1.8)	23.6 (2.4)
MVJH [^] , m	0.34 (0.04)	0.39 (0.08)*

* Body mass index

[^] Maximum vertical jump height

* control group > experimental group ($p = 0.0343$)

values for descriptive data appear in Table 2. Independent-samples t -tests did not reveal any significant differences between the experimental or control groups for age, height, weight, or body mass index. However, there was a significant difference in maximum vertical jump height between groups ($p = .0343$; experimental = 0.33 m (0.06); control = 0.39 m (0.08)). Maximum jump height was then included as a covariate in the mixed model ANOVA. However, it did not explain any additional variation, so it was not included in the ANOVA model. All statistical assumptions were met for the mixed-model ANOVAs.

Countermovement Jump (Retention Tests): Phase One (Table 3)

Frontal Plane Variables

The mixed-model ANOVA for the peak knee adduction moment indicated a significant interaction between group and time within phase one ($p = .0381$).

Table 3: Means (SD), Effect Sizes and Percentage Changes for Primary Variables for Countermovement Jump, Phase One.

		<i>Experimental Group</i>			<i>Control Group</i>		
		Baseline	Immediate Retention	Delayed Retention	Baseline	Immediate Retention	Delayed Retention
Peak adduction moment (Nm/kg)	Mean (SD)	0.55 (0.22)	0.44 (0.21) ^a	0.54 (0.19)	0.44 (0.24)	0.49 (0.23)	0.49 (0.24)
	Effect Size		-0.50	-0.05		0.23	0.22
	Change (%)		-19.7%	-1.7%		12.4%	12.3%
Peak abduction angle (°)	Mean (SD)	-10.1 (4.1)	-10.3 (4.8)	-11.0 (3.8) ^b	-7.9 (2.7)	-9.3 (4.8)	-9.6 (4.3) ^b
	Effect Size		0.04	0.21		0.37	0.48
	Change (%)		1.7%	8.0%		17.4%	21.3%
Peak extension moment (Nm/kg)	Mean (SD)	2.28 (0.61)	2.06 (0.47)	2.12 (0.57)	2.24 (0.48)	2.16 (0.37)	2.21 (0.36)
	Effect Size		-0.40	-0.27		-0.18	-0.07
	Change (%)		-9.5%	-7.1%		-3.4%	-1.4%
Knee excursion (°)	Mean (SD)	66.2 (13.6)	75.4 (15.6) ^c	75.9 (17.4) ^c	59.1 (12.3)	60.4 (12.8)	59.4 (10.9)
	Effect Size		-0.63	0.63		0.10	0.02
	Change (%)		13.9%	14.8%		2.2%	0.5%
Peak vertical GRF (%BW)	Mean (SD)	1.81 (0.41)	1.60 (0.39) ^d	1.62 (0.43) ^d	1.73 (0.41)	1.68 (0.34) ^d	1.72 (0.31) ^d
	Effect Size		-0.52	-0.45		-0.13	-0.04
	Change (%)		-11.4%	-10.5%		-2.7%	-0.7%

^a Significant interaction (p= .0381)

^b Significant time effect (p= .0339)

^c Significant interaction effect (p= .0004)

^d Significant time effect (p= .0310)

Fisher's LSD test indicated that the experimental group's mean value for peak knee adduction moment for the immediate retention test (0.44 Nm/kg; ES = -0.50) was less than their mean baseline value (0.55 Nm/kg; $p = .0175$) and their delayed retention test mean value (0.54 Nm/kg; $p = .0279$). The control group's mean values for peak knee adduction were similar across measures of time. The mixed-model ANOVA for peak knee abduction angle indicated a significant main effect for time ($p = .0339$) within phase one. Fisher's LSD test demonstrated that the overall group mean value for peak knee abduction angle (-10.3° ; ES = 0.38) for the delayed retention test was greater than the overall group mean baseline value (-9.0° ; $p = .0103$).

Sagittal Plane Variables

The mixed-model ANOVA for peak knee extension moment did not indicate any significant main effects for group ($p = .7697$) or time ($p = .0703$) or any significant interactions between group or time ($p = .4611$) within phase one. The mixed-model ANOVA for the knee excursion indicated a significant interaction between group and time ($p = .0004$) within phase one. Fisher's LSD test indicated that the experimental group's mean values for knee excursion at the immediate retention test (75.4° ; $p = <.0001$; ES = 0.63) and the delayed retention test (75.9° ; $p = <.0001$; ES = 0.63) were both greater than their mean baseline value (66.2°). The control group's mean values for knee excursion were similar across measures of time.

Peak hip flexion and ankle dorsiflexion joint angles during the landing phase were also investigated to aid in interpreting the overall sagittal plane joint

angular kinematics (Table 4). Effect sizes for peak hip flexion angle for the experimental group indicated a moderate effect size for an increase in peak hip flexion angle at the immediate retention test (ES = 0.65; 37% increase) and the delayed retention test (ES = 0.61; 35% increase) within phase one. Effect sizes for peak hip flexion angle for the control group indicated no effect for peak hip flexion at the immediate retention test (ES = 0.08; 4% increase) and the delayed retention test (ES = 0.09; 5% increase) within phase one. Effect sizes for peak ankle dorsiflexion angle for the experimental group indicated a moderate effect size for an increase in peak ankle dorsiflexion angle the immediate retention test (ES = 0.56; 12% increase) and a small effect for an increase in ankle dorsiflexion at the delayed retention test (ES = 0.33; 7% increase) within phase one. Effect sizes for peak ankle dorsiflexion angle for the control group indicated no effect for peak hip flexion at the immediate retention test (ES = -0.04; 2% decrease) and the delayed retention test (ES = -0.09; -4% decrease) within phase one.

Ground Reaction Force Variable

The mixed-model ANOVA for the peak vertical ground reaction force indicated a significant main effect for time ($p = .0310$) within phase one. Fisher's LSD test for time demonstrated that the overall mean value for peak vertical ground reaction force for the immediate retention test (1.64 %BW; $p = .0128$; ES = - 0.39) and the delayed retention test (1.67 %BW; $p = .0448$; ES = - 0.31) were less than the overall mean value at baseline (1.79 %BW).

Table 4: Means (SD) for Peak Hip Flexion and Ankle Dorsiflexion Angles for Countermovement Jump, Phase One.

	<i>Experimental Group</i>			<i>Control Group</i>		
	Baseline	Immediate Retention	Delayed Retention	Baseline	Immediate Retention	Delayed Retention
Peak hip flexion angle (°)	48.8 (28.5)	66.9 (27.0)	65.8 (27.1)	41.6 (22.3)	43.4 (21.5)	43.5 (20.0)
Peak ankle dorsiflexion angle (°)	14.2 (2.5)	15.8 (3.5)	15.2 (3.9)	12.4 (5.1)	12.2 (5.5)	12.0 (5.3)

Stop-jump Task (Transfer Test): Phase One (Table 5)

Approach Speed

The mixed-model ANOVA for approach speed did not indicate any significant main effects for group ($p = .4082$) or time ($p = .1503$) or any significant group and time interactions ($p = .6834$) within phase one. Table 6 displays the overall and group means and standard deviations for approach speed at baseline and transfer test.

Frontal Plane Variables

The mixed-model ANOVA for peak knee adduction moment did not indicate any significant main effects for group ($p = .4998$) or time ($p = .4023$) or any significant group and time interactions ($p = .2241$) within phase one. The mixed-model ANOVA for peak knee abduction angle indicated a significant main effect for time ($p = .0432$) within phase one. Overall both groups had a small increase in for peak abduction angle during the stop-jump transfer task from -13.3° to -14.3° ($ES = 0.17$).

Sagittal Plane Variables

The mixed-model ANOVA for peak knee extension moment indicated a significant main effect for time within phase one. Overall both groups had a small decrease in peak knee extension moment during the stop-jump transfer task from 2.53 Nm/kg to 2.65 Nm/kg ($p = .0005$; $ES = -0.22$). The mixed-model ANOVA for knee excursion did not indicate any significant main effects for group

Table 5: Means (SD), Effect Sizes and Percentage Changes for Primary Variables for Stop-jump task, Phase One.

		Experimental Group		Control Group	
		Baseline	Transfer	Baseline	Transfer
Peak adduction moment (Nm/kg)	Mean (SD)	0.83 (0.42)	0.77 (0.41)	0.70 (0.26)	0.72 (0.25)
	Effect Size		-0.16		0.05
	Change (%)		-8.0%		1.6%
Peak abduction angle (°)	Mean (SD)	-13.2 (5.4)	-13.5 (5.7) ^a	-13.4 (6.4)	-15.1 (6.0) ^a
	Effect Size		0.06		0.28
	Change (%)		2.4%		13.2%
Peak extension moment (Nm/kg)	Mean (SD)	2.63 (0.52)	2.50 (0.47) ^b	2.67 (0.66)	2.57 (0.60) ^b
	Effect Size		-0.28		-0.16
	Change (%)		-5.2%		-3.8%
Knee excursion (°)	Mean (SD)	45.9 (9.9)	47.7 (11.9)	50.6 (10.2)	49.5 (11.6)
	Effect Size		0.16		-0.10
	Change (%)		3.7%		-2.2%
Peak vertical GRF (%BW)	Mean (SD)	2.15 (0.72)	2.12 (0.75)	1.86 (0.52)	1.88 (0.58)
	Effect Size		-0.03		0.04
	Change (%)		-1.2%		1.0%

^a Significant time effect (p= .0432)

^b Significant time effect (p= .0005)

Table 6: Means (SD) for Approach Speed (m/s) for Stop-jump Task, Phase One.

		<i>Time</i>		
		Baseline	Transfer	
Group	Experimental	2.88 (0.34)	2.97 (0.48)	2.93 (0.41)
	Control	2.79 (0.28)	2.84 (0.29)	2.82 (0.28)
		2.84 (0.31)	2.91 (0.40)	

($p = .4461$) or time ($p = .7438$) or any significant interactions between group or time ($p = .1301$) within phase one.

Ground Reaction Force Variable

The mixed-model ANOVA for peak vertical ground reaction force did not indicate any significant main effects for group ($p = .2913$) or time ($p = .9661$) or any significant interactions between group or time ($p = .6613$) within phase one.

Countermovement Jump (Retention Tests): Phase Two (Table 7)

Frontal Plane Variables

The mixed-model ANOVA for peak knee adduction moment did not indicate any significant main effects for group ($p = .7270$) or time ($p = .1967$) or any significant interactions between group or time ($p = .1039$). The mixed-model ANOVA for peak knee abduction angle did not indicate any significant main effects for group ($p = .2210$) or time ($p = .1478$) or any significant interactions between group or time ($p = .2271$).

Table 7: Means (SD), Effect Sizes and Percentage Change for Primary Variables for Countermovement Jump, Phase Two.

		Experimental Group			Control Group		
		Baseline	Retention 1	Retention 2	Baseline	Retention 1	Retention 2
Peak adduction moment (Nm/kg)	Mean (SD)	0.55 (0.22)	0.48 (0.18)	0.53 (0.18)	0.44 (0.24)	0.49 (0.25)	0.56 (0.21)
	Effect Size		-0.32	-0.08		0.23	0.53
	Change (%)		-11.9%	-2.9%		12.8%	27.5%
Peak abduction angle (°)	Mean (SD)	-10.1 (4.1)	-10.2 (2.3)	-10.3 (4.1)	-7.9 (2.7)	-8.1 (4.0)	-10.1 (4.4)
	Effect Size		0.03	0.04		0.05	0.62
	Change (%)		0.9%	1.8%		2.1%	27.6%
Peak extension moment (Nm/kg)	Mean (SD)	2.28 (0.61)	2.08 (0.40)	2.15 (0.38)	2.24 (0.48)	2.29 (0.49)	2.25 (0.38)
	Effect Size		-0.39	-0.26		0.10	0.02
	Change (%)		-8.7%	-5.7%		2.2%	0.5%
Knee excursion (°)	Mean (SD)	66.2 (13.6) ^a	69.7 (16.3) ^a	71.7 (18.5) ^a	59.1 (12.3)	56.0 (10.9)	58.3 (10.4)
	Effect Size		0.22	0.34		-0.27	-0.07
	Change (%)		5.3%	8.3%		-5.3%	-1.4%
Peak vertical GRF (%BW)	Mean (SD)	1.81 (0.41)	1.64 (0.40) ^b	1.72 (0.38)	1.73 (0.41)	1.82 (0.42)	1.76 (0.39)
	Effect Size		-0.42	-0.22		0.20	0.07
	Change (%)		-9.4%	-4.9%		4.9%	1.5%

^a Significant group effect (p= .0373)

^b Significant interaction effect (p= .0378)

Sagittal Plane Variables

The mixed-model ANOVA for peak knee extension moment did not indicate any significant main effects for group ($p = .5919$) or time ($p = .5466$) or any significant interactions between group or time ($p = .2335$). The mixed-model ANOVA for knee excursion indicated a significant main effect for group.

Specifically, the overall experimental group's mean value for knee excursion (69.2° ; $ES = 0.84$) was significantly greater than the overall control group's mean value (57.8° ; $p = .0373$).

Again, peak hip flexion and ankle dorsiflexion joint angles during the landing phase were calculated to aid in interpreting the overall sagittal plane joint angular kinematics (Table 8). Effect sizes for the experimental group indicated a moderate effect size for an increase in peak hip flexion angle at retention test one ($ES = 0.72$; 41% increase) and retention test two ($ES = 0.78$; 45% increase). Effect sizes for peak hip flexion angle for the control group indicated no effect for peak hip flexion at retention test one ($ES = -0.13$; -2% decrease) and retention test two ($ES = 0.06$; 2% increase). Effect sizes for peak ankle dorsiflexion angle for the experimental group indicated no effect in peak ankle dorsiflexion angle at retention test one ($ES = -0.07$; -2% decrease) and retention test two ($ES = 0.04$; 1% increase). Effect sizes for peak ankle dorsiflexion for the control group indicated no effect for peak hip flexion at retention test one ($ES = -0.04$; 2% decrease) and a small effect for peak hip flexion at retention test two ($ES = 0.37$; 10% increase).

Table 8: Means (SD) for Peak Hip Flexion and Ankle Dorsiflexion Angles for Countermovement Jump, Phase Two.

	<i>Experimental Group</i>			<i>Control Group</i>		
	Baseline	Retention 1	Retention 2	Baseline	Retention 1	Retention 2
Peak hip flexion angle (°)	48.8 (28.5)	68.7 (26.6)	70.4 (26.7)	41.6 (22.3)	40.6 (20.3)	42.3 (18.8)
Peak ankle dorsiflexion angle (°)	14.2 (2.5)	14.0 (3.3)	14.3 (4.1)	12.4 (5.1)	12.0 (3.5)	13.6 (3.9)

Ground Reaction Force Variable

The mixed-model ANOVA for the peak vertical ground reaction force indicated a significant interaction between group and time ($p = .0378$). Fisher's LSD test indicated that the experimental group's mean value for peak vertical ground reaction force for retention test one (1.64 %BW; $p = .0158$; ES = - 0.42) was significantly less than their mean baseline value (1.81 %BW). The control group's mean values for peak vertical ground reaction force were similar across measures of time.

Stop-jump Task (Transfer Test): Phase Two (Table 9)

Approach Speed

The mixed-model ANOVA for approach speed did not indicate any significant main effects for group ($p = .2371$) or time ($p = .1836$) or any significant group and time interactions ($p = .3219$). Table 10 displays the overall and group means and standard deviations for approach speed at baseline and transfer test.

Frontal Plane Variables

The mixed-model ANOVA for peak knee adduction moment did not indicate any significant main effects for group ($p = .4438$) or time ($p = .4816$) or any significant group and time interactions ($p = .6411$). The mixed-model ANOVA for peak knee abduction angle did not indicate any significant main effects for group ($p = .8046$) or time ($p = .2017$) or any significant group and time interactions ($p = .5851$).

Table 9: Means (SD), Effect Sizes and Percentage Changes for Primary Variables for Stop-jump Task, Phase Two.

		<i>Experimental Group</i>		<i>Control Group</i>	
		Baseline	Transfer	Baseline	Transfer
Peak adduction moment (Nm/kg)	Mean (SD)	0.83 (0.42)	0.85 (0.40)	0.70 (0.26)	0.77 (0.35)
	Effect Size		0.03		0.22
	Change (%)		1.7%		9.6%
Peak abduction angle (°)	Mean (SD)	-13.2 (5.4)	-13.8 (6.4)	-13.4 (6.4)	-14.9 (7.0)
	Effect Size		0.10		0.22
	Change (%)		4.7%		11.3%
Peak extension moment (Nm/kg)	Mean (SD)	2.63 (0.52)	2.63 (0.45)	2.67 (0.66)	2.81 (0.65)
	Effect Size		0.02		0.22
	Change (%)		0%		5.3%
Knee excursion (°)	Mean (SD)	45.9 (9.9)	44.9 (9.8)	50.6 (10.2)	49.8 (10.6)
	Effect Size		-0.10		-0.08
	Change (%)		-2.2%		-1.7%
Peak vertical GRF (%BW)	Mean (SD)	2.15 (0.72)	2.15 (0.74)	1.86 (0.52)	1.95 (0.61)
	Effect Size		-0.01		0.16
	Change (%)		-0.2%		4.8%

Table 10: Means (SD) for Approach Speed (m/s) for Stop-jump Task, Phase Two.

		<i>Time</i>		
		Baseline	Transfer	
Group	Experimental	2.88 (0.34)	3.00 (0.42)	2.94 (0.38)
	Control	2.79 (0.28)	2.81 (0.23)	2.80 (0.25)
		2.84 (0.31)	2.90 (0.34)	

Sagittal Plane Variables

The mixed-model ANOVA for peak knee extension moment did not indicate any significant main effects for group ($p = .6250$) or time ($p = .1899$) or any significant group and time interactions ($p = .1412$). The mixed-model ANOVA for knee excursion did not indicate any significant main effects for group ($p = .2236$) or time ($p = .4126$) or any significant group and time interactions ($p = .9388$).

Ground Reaction Force Variable

The mixed-model ANOVA for peak vertical ground reaction force did not indicate any significant main effects for group ($p = .3252$) or time ($p = .4796$) or any significant interactions between group or time ($p = .5227$).

CHAPTER V: Discussion

This dissertation sought to examine the effects of jump training procedures aimed at improving lower extremity kinetics and kinematics in high-risk female recreational athletes during a jump-landing. The jump training procedures were centered around instructions and demonstrations that attempted to improve each participant's frontal plane knee alignment. In addition to the demonstrations and instructions, a full-length mirror was used to provide feedback to participants. During phase one, the jump training procedures were provided to each participant under the direction of the primary investigator to determine their immediate effects. The jump training procedures were then provided to participants through a home-based program (i.e., self practice) during phase two. In this phase, participants practiced on their own in front of a mirror using the same instructions provided during the instructional session. A control group, which performed a similar dosage of sham training during phase one and phase two, was included to determine the stability of countermovement and stop-jump performance over time. A secondary purpose of this study was to determine if any transfer occurred during either phase as a result of the jump training procedures.

The results of phase one partially supported our research hypotheses. During this phase, participants in the experimental group landed with smaller peak knee adduction moments and greater knee excursion. However, the reduction in peak knee adduction moment was only present during the immediate retention test, while the increase in knee excursion was observed at the

immediate and the delayed retention tests. No statistically significant changes were observed between groups for peak knee extension moment. In addition, a statistically significant time was observed for the peak vertical ground reaction force and peak knee abduction angle. The transfer test did not indicate any significant interactions between groups. However, statistically significant effects for time were demonstrated for peak knee extension moment and peak knee abduction angle in the transfer test. Similar to phase one, the results of phase two only partially supported our research hypotheses. After the home-based training, participants in the experimental group landed with a smaller peak vertical ground reaction force and greater knee excursion. No statistically significant changes were observed between groups for peak knee extension or adduction moments or peak knee abduction angle. The results of the transfer test did not support any transfer of skills to the stop-jump task.

Overall, the results suggest that the jump training procedures resulted primarily in increased motion about the sagittal plane without any subsequent increase in frontal plane knee motion. Although the jump training procedures were designed to minimize frontal plane motion, the results did not indicate any long-term reductions in frontal plane knee kinematics or kinetics. Furthermore, no significant long-term reductions in sagittal plane knee kinetics or peak vertical ground reaction forces were observed. Based on the entirety of the results, it appears that our jump training procedures would be inadequate to result in any significant reductions in ACL injury risk in female recreational athletes.

Phase One

Frontal Plane Effects

The results demonstrated that the jump training procedures resulted in an immediate 20% reduction in peak knee adduction moment for the experimental group. Other jump training procedures have also led to immediate reductions in knee adduction moments of similar magnitude (Mizner, Kawaguchi et al., 2008; Herman, Onate et al., 2009). Mizner et al. observed a 22% reduction in peak knee adduction moment during a drop-jump landing, while Herman et al. demonstrated a 40% reduction in knee abduction moment sampled at peak proximal tibial anterior shear force. In both of these studies, participants were provided with instructions and feedback regarding their frontal and sagittal plane knee alignment. In addition, Herman et al. also provided participants with video feedback that allowed participants to view the amount of varus-valgus motion present during their practice jumps. However, the immediate reduction of peak knee adduction moment observed in the immediate retention test in our study was not maintained in the delayed retention test. This finding may have partially been the result of the small increase in knee abduction angle that occurred during the delayed retention test. Landing with the knee in a more abducted position potentially could result in higher joint loading about the frontal plane. It should be noted that Mizner et al. nor Herman et al. performed long-term retention tests across days or weeks in their studies, so it is unknown whether the immediate changes seen in their studies would have been maintained without additional instruction and/or practice.

No significant interaction between group and time was observed for peak knee abduction angle despite the immediate reduction shown in peak knee adduction moment. One reason for this unexpected finding may be related to the dual task (i.e., grabbing the basketball) presented to our participants during the basketball rebound task used for baseline and retention tests. The additional requirement of participants to grab the ball while performing a jump landing may have resulted in participants being unable to direct their full attention on landing with less medial knee displacement. Several studies analyzing the effects of dual tasks have observed slower gait speeds in the gait of healthy adults when asked to perform a secondary task (Yogev-Seligmann, Hausdorff et al., 2008). Therefore, the addition of a secondary task, such as grabbing a basketball, may have reduced the amount of attention our participants were able to direct towards their frontal plane knee alignment. Furthermore, the results demonstrated that both the experimental and control group's peak knee abduction angles were greater (approximately 1-2°) during the delayed retention test compared to baseline. This finding was not expected, but may have resulted from fatigue following the numerous jumps performed during phase one. In addition, participants in the control group had relatively large percentage changes at both retention tests compared to the experimental group. This finding may illustrate that individuals that present with medial knee displacement may have a great predisposition to move within the frontal plane, especially when attempting to jump as high as possible. In this study, participants in the control group were instructed to "jump as high as possible" as a sham jump training intervention.

Contrary to our results, Mizner et al. (Mizner, Kawaguchi et al., 2008) demonstrated a statistically significant reduction of approximately 1° in peak knee abduction angles following their jump training procedures. The additional verbal feedback provided to participants after each practice trial in their study may have resulted in their positive finding.

Sagittal Plane Effects

Our jump training procedures also resulted in statistically significant increases in knee excursion during both retention tests. In general, participants in the experimental group increased the amount of knee excursion by 14-15%. Onate et al. (Onate, Guskiewicz et al., 2005) and Mizner et al. (Mizner, Kawaguchi et al., 2008) also demonstrated similar increases in knee excursion immediately following their jump training procedures. The results of their studies may not be too surprising given that both studies instructed participants to bend their knees more during jump-landings. However, we were able to achieve similar results without additional instructions aimed at increasing the amount of knee bend during the landing. Additionally, our results indicated that participants in the experimental group also landed with greater amounts of hip flexion and ankle dorsiflexion as a result of our jump training procedures. Altogether, these findings suggest that participants in the experimental group chose to move more within the sagittal plane when attempting to minimize medial knee displacement. Previous studies have illustrated that males tend to absorb the shock of jump landing with a greater hip and knee contribution, while females tend to absorb impact with more knee and ankle involvement (Decker, Torry et al., 2003).

Blackburn and Padua (Blackburn and Padua, 2008) have suggested that landing in a more flexed posture (i.e., less erect) may also be helpful in reducing risk of ACL injury. Therefore, the increases in sagittal plane hip and knee motion that occurred as a result of our jump training may improve the overall biomechanical risk profile of our participants as they pertain to ACL injuries.

No significant interaction between group and time was observed for peak knee extension moment despite the changes seen in sagittal plane hip, knee, and ankle kinematics. Therefore, the jump training procedures did not result in any significant reductions in peak knee extension moment. Herman et al. (Herman, Onate et al., 2009) also did not observe any significant reductions in knee extension moment, sampled at the time of peak proximal tibial anterior shear force, in their study. However, Mizner et al. (Mizner, Kawaguchi et al., 2008), did demonstrate a statistically significant reduction in peak knee extension moment following their jump training procedures. Peak knee extension moment has been demonstrated to be strongly correlated to proximal anterior tibial shear forces (Yu, Lin et al., 2006; Sell, Ferris et al., 2007). Therefore, a reduction in this kinetic variable is thought to be associated with a reduced ACL injury risk (Yu, Lin et al., 2006; Sell, Ferris et al., 2007).

Ground Reaction Force Effects

No significant interaction between group and time was observed for peak vertical ground reaction force. This finding was somewhat unexpected, especially given the significant increases in sagittal plane motion observed in the experimental group at the hip, knee, and ankle. However, a significant main

effect for time was observed and indicated that the baseline value for both groups was significantly greater than the values for both retention tests. However, percent changes demonstrated that the experimental group underwent reductions of 11% at both retention tests, while the control group only experienced a 3% and 1% reduction at the immediate and delayed retention tests, respectively. The lack of a statistically significant interaction may have occurred due to our relatively small sample size. Effect sizes and percentage change values suggest that the experimental group's reduction in peak vertical ground reaction force may have been clinically significant, but not statistically significant due to lack of power. We also should point out that we did not provide our participants with any instructions directed towards the forces associated with their landing. Numerous technique training studies have demonstrated the ability to produce an immediate statistically significant reduction in vertical ground reaction forces through verbal instruction and/or feedback directed at "landing softer" (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000; Onate, Guskiewicz et al., 2001; Cowling, Steele et al., 2003; Prapavessis, McNair et al., 2003; Onate, Guskiewicz et al., 2005; Cronin, Bressel et al., 2008; Mizner, Kawaguchi et al., 2008; Herman, Onate et al., 2009). In these studies have used a variety of jump-landing tasks, such as drop-jump landings (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000; Prapavessis, McNair et al., 2003; Mizner, Kawaguchi et al., 2008), countermovement jump-landings (Onate, Guskiewicz et al., 2001; Onate, Guskiewicz et al., 2005), stop-jump landings (Herman, Onate et al., 2009), and jump-landings after a volleyball spike (Cronin,

Bressel et al., 2008). The amount of reduction in peak vertical ground reaction force in studies using drop landings ranged from 13-27% and studies using countermovement jump-landings resulted in reductions of 18-24%. Another study that used the landing phase of a stop-jump task observed a 23% reduction (Herman, Onate et al., 2009), while a study that used the jump-landing immediately after a volleyball spike observed a 24% reduction (Cronin, Bressel et al., 2008).

Transfer Test

The results of the transfer test did not support our hypothesis; no transfer between the countermovement and stop-jump tasks occurred in phase one. The results did yield statistically significant effects for time for peak knee extension moment and peak knee abduction angle. In general, participants in both groups landed with smaller peak knee extension moments and greater knee abduction angles during phase one. Percentage change values indicated that peak knee extension moments decreased by 4-5% for both groups. Fatigue may have resulted in this significant time effect for peak knee extension moment.

Participants performed the stop-jump task at baseline and at the same time as the delayed retention test. In between baseline and the delayed retention test, participants in both groups performed three sets of five countermovement jumps during practice, another five countermovement jumps during the immediate retention test, and finally another two sets of five jumps (one set for each task) during the delayed retention test. The ANOVA for peak knee abduction angle indicated a statistically significant effect for time, indicating that both groups had

statistically significant increases in peak knee abduction during the transfer test. Percentage change values for peak knee abduction angle indicated that the control group exhibited a 13% increase in peak knee abduction angles (1.9° increase) compared to a 2% increase in the experimental group (0.3° increase). Based on these changes, one could argue that the control group exhibited a more clinically significant increase in peak knee abduction angle, although the interaction effect was not significant ($p = 0.1509$). This may have been the result of control participants attempting to jump higher during the stop-jump task due to their sham training, which instructed them to “jump as high as possible”.

Phase Two

Over the past several years, numerous studies have investigated the training effects of exercise programs designed to improve the landing patterns of athletes, particularly female athletes (Hewett, Stroupe et al., 1996; Myer, Ford et al., 2005; Pollard, Sigward et al., 2006; Myer, Ford et al., 2007; Kato, Urabe et al., 2008; Lim, Lee et al., 2009). These programs were implemented over four to eight week periods and typically included technique, strength, balance, and flexibility training. Baseline measures of motion analysis during various at-risk movements, such as drop-jump landings and stop-jump tasks, were performed and then follow-up analyses occurred immediately following the training program. These studies attempted to improve the biomechanical profiles of jump landings analyzing a variety of biomechanical factors associated with ACL injury risk. In the following sections, comparisons to their results will be made with common variables. In addition, two technique training studies analyzed the effects of their

training with follow-ups ranging from 1 week (Onate, Guskiewicz et al., 2005) to 3 months (Prapavessis, McNair et al., 2003). Therefore, comparisons to their results will also be made with common biomechanical variables for these studies.

Frontal Plane Effects

The implementation of a home-based program modeled after the initial jump-training procedures did not result in any significant changes in peak knee adduction moment or knee abduction angle. Based on these results, our short-term home-based program does not appear capable of reducing frontal plane knee kinetics or kinematics. This finding was not surprising based on the results following the instructional session, which indicated only a temporary reduction in peak knee adduction moment. Although the verbal instructions were aimed at reducing medial knee displacement, no statistically significant changes in peak abduction angles were observed in either retention test. Contrary to our findings, Hewett et al. (Hewett, Stroupe et al., 1996) demonstrated a 50% reduction in internal knee adduction moment at initial contact of a drop-jump landing in a small number of participants (n=4) as a result of their comprehensive jump training program. In a subsequent studies using similar training programs, Myer et al. (Myer, Ford et al., 2005; Myer, Ford et al., 2007) reported statistically significant, but relatively smaller reductions ranging from 13-21% in peak internal knee adduction moments during a drop-jump landing.

Only two of the aforementioned studies analyzed peak knee abduction angles and results were mixed. Kato et al. reported reductions in peak frontal plane angle of 37% and 59% during a stop-jump task after 2 weeks and 4 week

of training, respectively (Kato, Urabe et al., 2008). However, their results should be interpreted with caution, since their analysis was two-dimensional. A limitation of two-dimensional analyses of the knee is that frontal plane knee motion also contains measures of off-plane motion, most notably knee flexion. Therefore, changes in knee flexion could have presented as frontal plane changes. On the other hand, Pollard et al. did not report any significant change in peak knee abduction angle after injury prevention training (Pollard, Sigward et al., 2006). These results suggest that additional research is needed to determine the effects of training programs on peak knee abduction angles.

Our results may indicate that participants who present with medial knee displacement may be predisposed to both taking off and landing from a jump with greater frontal plane motion. Therefore, it may be beneficial for participants to also practice technique training for both phases of a countermovement jump (i.e., the takeoff and the landing). In addition, athletes who exhibit medial knee displacement may be unable to correct this malalignment without the use of other training modalities, such as strength training. Herman et al. (Herman, Onate et al., 2009) observed that athletes who received strength training were more responsive to video-assisted feedback compared to those who did not received strength training. They suggested that ACL injury prevention programs may be more effective when both technique and strength training were included in the program. However, Mizner et al. (Mizner, Kawaguchi et al., 2008) demonstrated that muscle strength was not predictive of short-term changes in landing mechanics following brief instruction. They suggest that other factors, such as

coordination of muscle firing, may be more important as they relate to temporary changes in landing mechanics associated with technique training.

Sagittal Plane Effects

Similar to the results of the instructional session, the home-based program did not result in any statistically significant reductions in peak knee extension moments contrary to our hypothesis. Likewise, Hewett et al. (Hewett, Stroupe et al., 1996) reported similar null findings pertaining to peak internal knee extension moment. In their study, female high school volleyball players participated in a six-week comprehensive jump training program aimed at improving their overall landing mechanics following a volleyball block jump. Lim et al.'s jump training program was the only program identified that resulted in a 19% reduction in peak knee internal extension moments during the jump-landing of a basketball rebound task (Lim, Lee et al., 2009). In their study, high school female basketball players participated in a program that was modeled around Mandelbaum's Prevent Injury and Enhance Performance Program (Mandelbaum, Silvers et al., 2005). Differences in study participants and movement tasks may have led to these mixed results. Our lack of other training modalities, supervision, and limited time frame may have also resulted in our null findings.

Similar to the results of phase one, participants in the experimental group continued to exhibit greater knee excursion compared to the control group. However, the amount of knee excursion was less compared to the amount observed during phase one (Tables 3 and 7). This small reduction in knee excursion during phase two may be explained by other sagittal plane changes

seen at the hip and ankle. After the home-based training, participants in the experimental group exhibited a greater effect size and percentage change values for peak hip flexion compared to phase one, while peak ankle dorsiflexion effect size and percent change values returned to baseline values. These results suggest that additional practice allowed our participants the opportunity to explore different ways of arriving at multi-joint solutions to jump landings. These solutions may occur as a result of adaptations over time, which may result in better athletic performance. Similar to our findings, Onate et al. (Onate, Guskiewicz et al., 2005) also demonstrated increased knee excursion during the landing phase of a basketball rebound task following their jump training instructions both during immediate retention and one-week retention tests. The magnitude of their changes in knee excursion as a result of video-feedback were much larger, ranging from 53% to 101%. In their study, participants were instructed to land with approximately 90° of maximum hip and knee flexion. Therefore, the larger percentage changes seen in their study appear directly linked to their instructions. The practicality of instructing athletes to land with a maximum hip and knee flexion of 90° remains unknown, especially in terms of potential injury risk and athletic performance.

Ground Reaction Force Effects

Participants in the experimental group landed with a statistically significant reduction of 9% in peak vertical ground reaction forces during retention test one, compared to a non-statistically significant reduction of 5% during retention test two. These results suggest that our training instructions were capable of

resulting in only a temporary reduction in peak vertical ground reaction force.

Olate et al. (Olate, Guskiewicz et al., 2005) have demonstrated that technique training procedures using video-feedback were capable of demonstrating carryover of reductions in peak vertical ground reaction force after one week of no practice. In their study, a checklist was provided to each participant providing information regarding the following biomechanical characteristics: both feet on the ground at the same time during at initial contact, frontal plane knee alignment, foot position relative to the body (i.e., whether or not feet were shoulder-width apart), foot motion during landing (i.e., whether or not participants landed on toes rolling towards heels), and amount of hip and knee flexion at initial contact and total amount of hip and knee flexion throughout the landing. In addition, participants were asked to land as softly as possible. Unfortunately, due to the study's design, it is unknown which aspects of the technique training resulted in the observed reductions in peak vertical ground reaction forces.

Prapavessis et al. (Prapavessis, McNair et al., 2003) were the only researchers identified that performed long-term retention tests to determine whether temporary changes in peak vertical ground reaction forces were maintained three months following initial training. In their study, school age children (mean age of 9 years) were unable to maintain temporary reductions in peak vertical ground reaction force as a result of their instructions. Hewett et al. (Hewett, Stroupe et al., 1996) were the only researchers identified that investigated changes in peak vertical ground reaction following a comprehensive jump training program. Their results demonstrated a 22% reduction in peak vertical

ground reaction force as a result of their jump training program. Based on these results, it is unknown whether short-term changes in peak vertical ground reaction forces are maintained at long-term follow-ups.

Transfer Test

The results of the transfer test for phase two was similar to the findings of phase one and did not support our research hypotheses. In addition, no effects of time were present for any of the variables analyzed in the study, which reflected that other factors (e.g., fatigue, learning) most likely did not occur between baseline and transfer tests.

Motor Learning Principles

Early studies analyzing the effects of technique training focused primarily on verbal instruction as a way to reduce peak vertical ground reaction forces (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000; Prapavessis, McNair et al., 2003). The instructions used in these studies focused on four key elements of ankle and knee motion during the landing phase of a drop-jump landing. Although their results demonstrated temporary reductions in peak vertical ground reaction forces, their instructions did not result in long-term changes (Prapavessis, McNair et al., 2003). It is quite possible that the verbal instructions used in their study overloaded the participant's attentional capacity and constrained their motor systems as a result of internal foci of attention. Therefore, we attempted to improve the delivery of our instructions by providing one to two key elements (i.e., knee over toes, avoid inward knee movement), while focusing the learner's attention on an external focus. Although our

research design does not enable us to draw the conclusion that our instructions were superior, we feel that we incorporated instructions that were based on current motor learning principles.

Previous studies (Onate, Guskiewicz et al., 2005; Mizner, Kawaguchi et al., 2008) have also cofounded the effects of multiple variables (i.e., instruction, demonstrations, and feedback) that motor behavior research has shown to be influential in performance. Although these studies represent real-world clinical application, it remains unknown as to what variable or combination of variables resulted in the temporary changes seen in landing mechanics.

Additionally, the majority of early research of technique training were limited to instruction. Augmented feedback may enhance motor learning by providing athletes with more individualized information regarding their landing mechanics. Video-assisted feedback has been utilized and shown to be effective in altering the landing patterns of athletes (Onate, Guskiewicz et al., 2005; Herman, Onate et al., 2009). However, the feasibility of individualized videotape review for each participant of an ACL injury prevention program must be questioned. Therefore, video-assisted feedback may be more useful in clinical settings where an athlete-to-clinician ratio of 1 to 1 is more practical. We chose to provide participants with feedback through the use of a mirror due to their common placement in clinical and gym settings. The advantages of a mirror is that they are relatively inexpensive, require minimal to no set up time, and allow the athlete the ability to incorporate the use of a mirror in a home based environment to practice jump landings. Despite these advantages, wide-scale

implementation of a mirror in ACL injury prevention programs may be limited to certain sports and settings. In addition, mirrors are limited in that they are primarily limited to providing visual feedback about frontal plane motion. In contrast, video replay is capable of providing both frontal and sagittal plane feedback. Additionally, we directed participants to focus on their image in the mirror as a way of providing an external focus. Research concerning the focus of the learner's attention (i.e., internal vs. external) has determined that an external focus of attention results in improved performance and learning (Wulf, McNevin et al., 2001; Wulf and Su, 2007). Our results may provide some preliminary evidence for the use of mirrors during technique training of jump-landings, although it is impossible to determine their individual effectiveness due to our study's design. Previous research analyzing the benefits of mirror feedback for learning of weightlifting and Pilates skills in beginners have provided conflicting results (Sewall, Reeve et al., 1988; Lynch, Chalmers et al., 2009). Sewall et al. (Sewall, Reeve et al., 1988) reported that mirror feedback resulted in improved performance of a power clean movement for participants compared to a control group who received only videotaped instruction. However, Lynch et al. (Lynch, Chalmers et al., 2009) did not observe any additional benefit of providing participants with mirror feedback when learning a Pilates skill. Therefore, more research into the potential benefits of a mirror as a way to provide athletes with additional information about their landing mechanics is needed.

Transfer

To our knowledge, this is the first technique training study to assess for the presence of transfer as a result of jump training procedures. The results of this study indicated that no transfer of jump-landing biomechanics occurred between countermovement jump-landings and the initial jump-landing phase of the stop-jump task. However, readers should take caution when interpreting these results due to the relatively small and moderate effects within the sagittal plane that occurred as a result of our training. Additional research is needed in this area to strengthen the results of this study. Despite this limitation, our results suggest that ACL injury prevention programs should include a variety of agility, jumping, running, and sport-specific tasks. These results provide evidence supporting the overall structure of two prevention programs, Sportsmetrics™ and The Prevention injury and Performance Program. Both of these programs include a wide variety of tasks as part of their programs and have led to reductions in ACL injuries in athletic populations (Hewett, Lindenfeld et al., 1999; Mandelbaum, Silvers et al., 2005; Gilchrist, Mandelbaum et al., 2008). Furthermore, motor learning studies suggest that the magnitude of transfer is typically small (Cormier and Hagman, 1987). Therefore, even if transference between tasks is possible, potential transfer between various jump-landing biomechanics may not result in clinically important carryover in biomechanical risk factors.

Performance

A potential side-effect of any jump-training procedures are adverse effects as they relate to performance (e.g., decrease in jump height). In our study, participants were able to achieve 80% of their maximum jump height during the basketball rebound task at all visits indicating that the jump capability was not affected by our jump training procedures. In addition, approach speed for the stop-jump task was similar between baseline and transfer test during both phases of the study. This may also provide additional support that our jump training procedures did not result in decreased performance (i.e., slower approach speed). Mizner et al. (Mizner, Kawaguchi et al., 2008) have reported similar findings, noting no major adverse effects as their jump training procedures related to performance.

Limitations

A limitation of this study is the sample size. An *a priori* power analysis was performed to provide power at 80% for large effects (i.e., effect size > 0.8). We selected our effect size based on findings of a prospective study that indicated a large effect (effect size = 1.2) for peak knee abduction moment differences between athletes predicted to be at low and high risk for ACL injuries (Hewett, Myer et al., 2005). In that study, peak knee abduction moment alone was able to predict risk of ACL injury with a sensitivity of 78% and specificity of 73%. Therefore, small and moderate effects found in the present study may not have been statistically significant with the sample size used. Another limitation of the study is the amount of variation within and between participants for the

countermovement jump task. A study analyzing the reliability of the countermovement jump task indicated that the countermovement jump task was less reliable and more varied (Milner, Tate et al., 2010) compared to drop-jump landings used by other investigators (Ford, Myer et al., 2007; Mizner, Kawaguchi et al., 2008). This increase in variation may have resulted in less statistical power, which could have resulted in type II errors. The results of this study were also limited to female recreational athletes. It is unknown whether any changes attributed to the jump training procedures used in this study would result in positive changes in other athletic populations (i.e., adolescent sports, collegiate athletes). Another potential limitation is related to use of the countermovement jump rebounding task as our primary task. Although almost all participants participated in a sport involving a ball, only 31% participated in basketball. Therefore, the task of rebounding a ball may have been new to some individuals. However, ample practice was provided for participants to allow them to become comfortable with the basketball rebound task. The primary investigator judged each participant who completed the study as being able to perform the task as requested.

Future Directions

Future research should combine the jump-training procedures with additional instructions aimed at reducing ground reaction forces associated with jump-landings. The immediate changes that occurred as a result of our frontal plane based commands resulted not only in positive changes in the frontal plane, but also in a more flexed posture within the sagittal plane. The jump training

instructions may eliminate the need for additional instructions focused on increasing knee bend and may allow the learner to focus on other task-specific skills (e.g. decrease ground reaction forces). Previous studies have demonstrated significant temporary reductions in peak ground reaction forces with the use of verbal instruction alone (Prapavessis and McNair, 1999; McNair, Prapavessis et al., 2000; Prapavessis, McNair et al., 2003). Therefore, additional reductions in peak ground reaction forces combined with a more flexed posture and reductions in frontal plane loading of the knee may result in a more favorable biomechanical profile as it relates to ACL injury risk. Future research is also needed to determine if our protocol or a similar protocol based on technique training alone is capable of resulting in long-term changes in lower extremity biomechanics if implemented for a longer duration (i.e., six weeks) and with more supervision. In our study, participants who received the jump training instructions were only provided feedback through the use of the mirror. Additional feedback from a clinician or coach may provide additional information that may be useful for the athlete. Additionally, a greater period of practice and more supervised practice may result in additional improvement in their jump landing mechanics. Finally, future studies should also determine whether programs that include strength training combined with technique training are capable of resulting in improved lower extremity biomechanics during jump-landings and other sports-related tasks (e.g., side-cut, single-leg landings). These type of studies may provide more support for initial evidence presented by Herman et al., which suggested that athletes that received strength training were

more responsive to technique training compared to similar athletes that did not received any strength training.

Conclusion

Our jump training procedures resulted in several temporary kinetic and kinematic changes of the lower extremity during a jump-landing. However, these changes most likely require additional practice and supervision over a longer period of time (e.g., six weeks or longer). Additionally, our results suggest that athletes may change their multi-joint solution over time with practice. Furthermore, the combination of technique training with other modalities, such as strength, plyometric and balance training, may result in greater long-term changes in landing mechanics, thus reducing ACL injury risk. In terms of transfer, our instructional methods alone were not capable of transfer to another sport-specific task. Therefore, the inclusion of a variety of drills and tasks is recommended in ACL injury prevention programs.

LIST OF REFERENCES

- Agel, J., E. A. Arendt and B. Bershadsky (2005). Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: a 13-year review. Am J Sports Med **33**: 524-530.
- Agel, J., D. E. Olson, R. Dick, E. A. Arendt, S. W. Marshall, et al. (2007). Descriptive epidemiology of collegiate women's basketball injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. J Athl Train **42**: 202-210.
- Arendt, E. and R. Dick (1995). Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. Am J Sports Med **23**: 694-701.
- Arendt, E. A., J. Agel and R. Dick (1999). Anterior Cruciate Ligament Injury Patterns Among Collegiate Men and Women. J Athl Train **34**: 86-92.
- Behn, A. and E. Ur (2006). The obesity epidemic and its cardiovascular consequences. Curr Opin Cardiol. **21**: 353-360.
- Bell, D. R., D. A. Padua and M. A. Clark (2008). Muscle strength and flexibility characteristics of people displaying excessive medial knee displacement. Arch Phys Med Rehabil **89**: 1323-1328.
- Berns, G. S., M. L. Hull and H. A. Patterson (1992). Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. J Orthop Res **10**: 167-176.
- Blackburn, J. T. and D. A. Padua (2008). Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. Clin Biomech **23**: 313-319.

- Boden, B. P., G. S. Dean, J. A. Feagin, Jr. and W. E. Garrett, Jr. (2000). Mechanisms of anterior cruciate ligament injury. Orthopedics **23**: 573-578.
- Cappozzo, A., A. Cappello, U. Della Croce and F. Pensalfini (1997). Surface-marker cluster design criteria for 3-D bone movement reconstruction. IEEE Trans Biomed Eng **44**: 1165-1174.
- Chappell, J. D., B. Yu, D. T. Kirkendall and W. E. Garrett (2002). A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. Am J Sports Med **30**: 261-267.
- Chiviawosky, S. and G. Wulf (2005). Self-controlled feedback is effective if it is based on the learner's performance. Res Q Exerc Sport **76**: 42-48.
- Cohen, J. (1988). Statistical power analysis for the behavioral sciences. Hillsdale, NJ, Lawrence Erlbaum Associates.
- Cormier, S. M. and J. D. Hagman (1987). Transfer of learning: Contemporary research applications. New York, NY, Academic Press.
- Cowling, E. J., J. R. Steele and P. J. McNair (2003). Effect of verbal instructions on muscle activity and risk of injury to the anterior cruciate ligament during landing. Br J Sports Med **37**: 126-130.
- Cronin, J. B., E. Bressel and L. Fkinn (2008). Augmented feedback reduces ground reaction forces in the landing phase of the volleyball spike jump. J Sport Rehabil **17**: 148-159.
- Decker, M. J., M. R. Torry, D. J. Wyland, W. I. Sterett and J. Richard Steadman (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. Clin Biomech **18**: 662-669.

- Dempster, W. T. (1955). Space requirements of the seated operator. Wright-Patterson Air Force Base, OH.
- Ekegren, C. L., W. C. Miller, R. G. Celebrini, J. J. Eng and D. L. Macintyre (2009). Reliability and validity of observational risk screening in evaluating dynamic knee valgus. J Orthop Sports Phys Ther **39**: 665-674.
- Ford, K. R., G. D. Myer and T. E. Hewett (2003). Valgus knee motion during landing in high school female and male basketball players. Med Sci Sports Exerc **35**: 1745-1750.
- Ford, K. R., G. D. Myer and T. E. Hewett (2007). Reliability of landing 3D motion analysis: implications for longitudinal analyses. Med Sci Sports Exerc **39**: 2021-2028.
- Ford, K. R., G. D. Myer, R. L. Smith, R. M. Vianello, S. L. Seiwert, et al. (2006). A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. Clin Biomech **21**: 33-40.
- Ford, K. R., G. D. Myer, H. E. Toms and T. E. Hewett (2005). Gender differences in the kinematics of unanticipated cutting in young athletes. Med Sci Sports Exerc **37**: 124-129.
- Gervais, P. L. (1997). Movement changes in landings from a jump as a result of instruction in children. Coaching and Sport Science Journal **2**: 11-16.
- Gilchrist, J., B. R. Mandelbaum, H. Melancon, G. W. Ryan, H. J. Silvers, et al. (2008). A randomized controlled trial to prevent noncontact anterior

- cruciate ligament injury in female collegiate soccer players. Am J Sports Med **36**: 1476-1483.
- Granan, L. P., R. Bahr, K. Steindal, O. Furnes and L. Engebretsen (2008).
Development of a national cruciate ligament surgery registry: the
Norwegian National Knee Ligament Registry. Am J Sports Med **36**: 308-
315.
- Griffin, L. Y., J. Agel, M. J. Albohm, E. A. Arendt, R. W. Dick, et al. (2000).
Noncontact anterior cruciate ligament injuries: risk factors and prevention
strategies. J Am Acad Orthop Surg **8**: 141-150.
- Griffin, L. Y., M. J. Albohm, E. A. Arendt, R. Bahr, B. D. Beynnon, et al. (2006).
Understanding and preventing noncontact anterior cruciate ligament
injuries: a review of the Hunt Valley II meeting, January 2005. Am J Sports
Med **34**: 1512-1532.
- Hebert, E. P. and D. Landin (1994). Effects of a learning model and augmented
feedback on tennis skill acquisition. Res Q Exerc Sport **65**: 250-257.
- Herman, D. C., J. A. Onate, P. S. Weinhold, K. M. Guskiewicz, W. E. Garrett, et
al. (2009). The effects of feedback with and without strength training on
lower extremity biomechanics. Am J Sports Med **37**: 1301-1308.
- Herman, D. C., P. S. Weinhold, K. M. Guskiewicz, W. E. Garrett, B. Yu, et al.
(2008). The effects of strength training on the lower extremity
biomechanics of female recreational athletes during a stop-jump task. Am
J Sports Med **36**: 733-740.

- Hewett, T. E., K. R. Ford and G. D. Myer (2006). Anterior cruciate ligament injuries in female athletes: Part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. Am J Sports Med **34**: 490-498.
- Hewett, T. E., T. N. Lindenfeld, J. V. Riccobene and F. R. Noyes (1999). The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med **27**: 699-706.
- Hewett, T. E., G. D. Myer, K. R. Ford, R. S. Heidt, Jr., A. J. Colosimo, et al. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med **33**: 492-501.
- Hewett, T. E., S. J. Shultz and L. Y. Griffin, Eds. (2007). Theories on how neuromuscular intervention programs may influence ACL injury rates. Understanding and Preventing Noncontact ACL Injuries. Champaign, IL, Human Kinetics.
- Hewett, T. E., A. L. Stroupe, T. A. Nance and F. R. Noyes (1996). Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med **24**: 765-773.
- Janelle, C. M., J. Kim and R. N. Singer (1995). Subject-controlled performance feedback and learning of a closed motor skill. Percept Mot Skills **81**: 627-634.
- Kato, S., Y. Urabe and K. Kawamura (2008). Alignment control exercise changes lower extremity movement during stop movements in female basketball players. Knee **15**: 299-304.

- Kernodle, M. W. and L. G. Carlton (1992). Information feedback and the learning multiple-degree-of-freedom activities. J Mot Behav **24**: 187-196.
- Kernozek, T. W., M. R. Torry, V. A. N. H. H, H. Cowley and S. Tanner (2005). Gender differences in frontal and sagittal plane biomechanics during drop landings. Med Sci Sports Exerc **37**: 1003-1012.
- Krosshaug, T., A. Nakamae, B. P. Boden, L. Engebretsen, G. Smith, et al. (2007). Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. Am J Sports Med **35**: 359-367.
- Lim, B. O., Y. S. Lee, J. G. Kim, K. O. An, J. Yoo, et al. (2009). Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. Am J Sports Med **37**: 1728-1734.
- Lind, M., F. Menhert and A. B. Pedersen (2009). The first results from the Danish ACL reconstruction registry: epidemiologic and 2 year follow-up results from 5,818 knee ligament reconstructions. Knee Surg Sports Traumatol Arthrosc **17**: 117-124.
- Lynch, J. A., G. R. Chalmers, K. M. Knutzen and L. T. Martin (2009). Effect on performance of learning a pilates skill with or without a mirror. J Bodyw Mov Ther **13**: 283-290.
- Mahler, D. A., V. F. Froelicher, N. H. Miller and T. D. York (1995). ACSM's Guidelines for exercise testing and prescription. Media, PA, Williams & Wilkins.

- Malinzak, R. A., S. M. Colby, D. T. Kirkendall, B. Yu and W. E. Garrett (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. Clin Biomech (Bristol, Avon) **16**: 438-445.
- Manal, K., I. McClay, S. Stanhope, J. Richards and B. Galinat (2000). Comparison of surface mounted markers and attachment methods in estimating tibial rotations during walking: an in vivo study. Gait Posture **11**: 38-45.
- Mandelbaum, B. R., H. J. Silvers, D. S. Watanabe, J. F. Knarr, S. D. Thomas, et al. (2005). Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med **33**: 1003-1010.
- Markolf, K. L., D. M. Burchfield, M. M. Shapiro, M. F. Shepard, G. A. Finerman, et al. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. J Orthop Res **13**: 930-935.
- Marshall, S. W., D. Padua and M. McGrath (2007). Incidence of ACL Injury. Understanding and Preventing Noncontact ACL Injuries. T. E. Hewett, S. J. Shultz and L. Y. Griffin. Champaign, IL, Human Kinetics: 5-29.
- McCullagh, P. and J. K. Caird (1990). Correct and learning models and the use of model knowledge of results in the acquisition and retention of a motor skill. J Hum Mov Stud **18**: 107-116.
- McCullagh, P. and K. N. Meyer (1997). Learning versus correct models: influence of model type on the learning of a free-weight squat lift. Res Q Exerc Sport **68**: 56-61.

- McCullagh, P. and M. R. Weiss (2002). Observational Learning: The forgotten psychological method in sport psychology. Exploring sport and exercise psychology. J. L. Van Raalte and B. W. Brewer. Washington, D.C., American Psychological Association: 131-149.
- McIlroy, W. E. and B. E. Maki (1997). Preferred placement of the feet during quiet stance: development of a standardized foot placement for balance testing. Clin Biomech **12**: 66-70.
- McLean, S. G., J. T. Andrish and A. J. van den Bogert (2005). Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. Am J Sports Med **33**: 1106; author reply 1106-1107.
- McLean, S. G., K. B. Walker and A. J. van den Bogert (2005). Effect of gender on lower extremity kinematics during rapid direction changes: an integrated analysis of three sports movements. J Sci Med Sport **8**: 411-422.
- McNair, P. J. and R. N. Marshall (1994). Landing characteristics in subjects with normal and anterior cruciate ligament deficient knee joints. Arch Phys Med Rehabil **75**: 584-589.
- McNair, P. J. and H. Prapavessis (1999). Normative data of vertical ground reaction forces during landing from a jump. J Sci Med Sport **2**: 86-88.
- McNair, P. J., H. Prapavessis and K. Callender (2000). Decreasing landing forces: effect of instruction. Br J Sports Med **34**: 293-296.
- McNevin, N. H., C. H. Shea and G. Wulf (2003). Increasing the distance of an external focus of attention enhances learning. Psychol Res **67**: 22-29.

- Milner, C. E., J. J. Tate and C. Westlake (2010). Test-retest reliability of knee biomechanics during countermovement jump landings. Med Sci Sports Exerc **42**: 680.
- Mizner, R. L., J. K. Kawaguchi and T. L. Chmielewski (2008). Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. J Orthop Sports Phys Ther **38**: 353-361.
- Myer, G. D., K. R. Ford, J. L. Brent and T. E. Hewett (2007). Differential neuromuscular training effects on ACL injury risk factors in "high-risk" versus "low-risk" athletes. BMC Musculoskelet Disord **8**: 39.
- Myer, G. D., K. R. Ford and T. E. Hewett (2004). Rationale and Clinical Techniques for Anterior Cruciate Ligament Injury Prevention Among Female Athletes. J Athl Train **39**: 352-364.
- Myer, G. D., K. R. Ford, J. P. Palumbo and T. E. Hewett (2005). Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. J Strength Cond Res **19**: 51-60.
- Myklebust, G., L. Engebretsen, I. H. Braekken, A. Skjølberg, O. E. Olsen, et al. (2003). Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. Clin J Sport Med **13**: 71-78.
- Nagano, Y., H. Ida, M. Akai and T. Fukubayashi (2007). Gender differences in knee kinematics and muscle activity during single limb drop landing. Knee **14**: 218-223.

- Olsen, O. E., G. Myklebust, L. Engebretsen and R. Bahr (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am J Sports Med **32**: 1002-1012.
- Olsen, O. E., G. Myklebust, L. Engebretsen, I. Holme and R. Bahr (2005). Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. BMJ **330**: 449.
- Onate, J. A., K. M. Guskiewicz, S. W. Marshall, C. Giuliani, B. Yu, et al. (2005). Instruction of jump-landing technique using videotape feedback: altering lower extremity motion patterns. Am J Sports Med **33**: 831-842.
- Onate, J. A., K. M. Guskiewicz and R. J. Sullivan (2001). Augmented feedback reduces jump landing forces. J Orthop Sports Phys Ther **31**: 511-517.
- Pappas, E., M. Hagins, A. Sheikhzadeh, M. Nordin and D. Rose (2007). Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. Clin J Sport Med **17**: 263-268.
- Park, I. and R. W. Schutz (1999). "Quick and Easy" Formulae for Approximating Statistical Power in Repeated Measures ANOVA. Measurement in Physical Education and Exercise Science **3**: 249-270.
- Payton, C. J. and R. M. Bartlett, Eds. (2008). Biomechanical Evaluation of Movement in Sport and Exercise. Motion Analysis Using Video. New York, NY, Routledge.
- Pollard, C. D., S. M. Sigward, S. Ota, K. Langford and C. M. Powers (2006). The influence of in-season injury prevention training on lower-extremity

- kinematics during landing in female soccer players. Clin J Sport Med **16**: 223-227.
- Prapavessis, H. and P. J. McNair (1999). Effects of instruction in jumping technique and experience jumping on ground reaction forces. J Orthop Sports Phys Ther **29**: 352-356.
- Prapavessis, H., P. J. McNair, K. Anderson and M. Hohepa (2003). Decreasing landing forces in children: the effect of instructions. J Orthop Sports Phys Ther **33**: 204-207.
- Rose, D. J. and R. W. Christina (2006). Augmented Feedback and Motor Learning. San Francisco, CA, Benjamin Cummings.
- Schmidt, R. A. and T. D. Lee (2005). Motor Control and Learning: A Behavioral Emphasis. Champaign, IL, Human Kinetics.
- Schmidt, R. A. and C. A. Wrisberg (2008). Motor Learning and Performance: A situation-based learning approach. Champaign, IL, Human Kinetics.
- Sell, T. C., C. M. Ferris, J. P. Abt, Y. S. Tsai, J. B. Myers, et al. (2007). Predictors of proximal tibia anterior shear force during a vertical stop-jump. J Orthop Res **25**: 1589-1597.
- Sewall, L. P., T. G. Reeve and R. A. Day (1988). Effect of concurrent visual feedback on acquisition of a weightlifting skill. Percept Mot Skills **67**: 715-718.
- Shin, C. S., A. M. Chaudhari and T. P. Andriacchi (2009). The effect of isolated valgus moments on ACL strain during single-leg landing: a simulation study. J Biomech **42**: 280-285.

- Shultz, S. J., R. J. Schmitz and A. D. Nguyen (2008). Research Retreat IV: ACL injuries-the gender bias: April 3-5, 2008 Greensboro, NC. J Athl Train **43**: 530-531.
- USDHHS (1996). Physical activity and health: A report of the Surgeon General. C. f. D. C. a. P. United States Department of Health and Human Services. Atlanta, GA.
- van den Bogert, A. J. and S. G. McLean (2006). Comment: effect of fatigue on knee kinetics and kinematics in stop-jump tasks. Am J Sports Med **34**: 312-315; author reply 313-315.
- Winter, D. A. (1990). Biomechanics and Motor Control of Human Movement. New York, NY, John Wiley & Sons.
- Withrow, T. J., L. J. Huston, E. M. Wojtys and J. A. Ashton-Miller (2006). The effect of an impulsive knee valgus moment on in vitro relative ACL strain during a simulated jump landing. Clin Biomech **21**: 977-983.
- Wulf, G., N. McNevin and C. H. Shea (2001). The automaticity of complex motor skill learning as a function of attentional focus. Q J Exp Psychol A **54**: 1143-1154.
- Wulf, G. and J. Su (2007). An external focus of attention enhances golf shot accuracy in beginners and experts. Res Q Exerc Sport **78**: 384-389.
- Wulf, G., M. Weigelt, D. Poulter and N. McNevin (2003). Attentional focus on suprapostural tasks affects balance learning. Q J Exp Psychol A **56**: 1191-1211.

- Yogev-Seligmann, G., J. M. Hausdorff and N. Giladi (2008). The role of executive function and attention in gait. Mov Disord **23**: 329-342.
- Yu, B., C. F. Lin and W. E. Garrett (2006). Lower extremity biomechanics during the landing of a stop-jump task. Clin Biomech **21**: 297-305.

APPENDICES

Appendix A. IRB Form for Control Group.

INFORMED CONSENT FORM The Performance and Learning Effects of Jump-Training on Jump Landing Technique in Female Recreational Athletes

Principal Investigator: Jeremiah Tate, PT, MS

Address: Dept of Exercise, Sport & Leisure Studies
University of Tennessee, 1914 Andy Holt Avenue, HPER 136
Knoxville, TN 37966

Phone: (865) 974-2091 (lab); (423) 883-5586 (mobile)

Purpose

You are invited to take part in a research study entitled “The Performance and Learning Effects of Jump-Training on Jump Landing Technique in Female Recreational Athletes”. This study aims to find out whether movement patterns in female athletes can be changed based on jump-training. This study involves four visits to our laboratory over a three-week duration. You will also be asked to complete two additional practice sessions lasting approximately 15 minutes each between the first and second laboratory visits.

You have been invited to take part in this study because you are a currently healthy recreational female athlete between the ages of 18-30. Also, you have not had any surgeries or recent injuries in the last six months that will affect your jumping and running ability. You should not participate in this study if you have a history of ACL injury or if you have ever participated in an ACL injury prevention program prior to this testing.

If you meet these criteria and agree to participate, we will measure your body mass index (a combination of height and weight) to make sure that it is below the limit of 30 for inclusion in our study. If you do not meet all of these criteria or choose not to participate in the study, your visit will end.

Laboratory Visits

1. Screening

If you are below the limit for body mass index, you will stay at the lab for 30 minutes for screening. The screening will determine if you are likely to benefit from our jump-training program. You will need to wear the sports bra, shorts, and tennis shoes that we asked you to bring with you. First, you will ride a stationary bike for five minutes and stretch your thigh and calf muscles to warm-up. I will help guide you through these stretches.

Next, I will measure how high you can jump using a Vertec jump measuring device. You will practice twice and then jump as high as you can three times. Next you will perform three jumps where you reach up and grab a basketball that is connected to a retractable string. The ball will be at 80% of your maximum jump height. Your body will be videotaped during these jumps (your face will not be recorded). I will review the video to see whether you may benefit from our jump-training. If you meet the screening criterion, then you will be scheduled to return to the lab in the near future for further data

collection. If the video indicates that you would not benefit from our jump-training, then your visit will end.

2. First data collection visit

The second lab visit will last approximately two hours. You will change into a pair of shorts, socks, and sandals that we provide. You will then have small silver balls attached to your waist, hips, legs and feet using medical tape and plastic shells. These will not interfere with your ability to jump and run. The cameras in our lab record the position of these balls as you jump, run and cut in the laboratory space. We will take some measurements of you standing still first.

Next, you will perform five good attempts at the following sports skills: stationary jump and four-step jump. You will grab the hanging ball in both of the jumps. I will demonstrate each movement and you will be able to practice it until you feel comfortable with the task. Then you will perform the task for data collection. You will be able to rest as much as you need.

Next, you will do the jump-training. You will do three sets of jumps, with eight jumps in each set. You will take a 20 second break between each jump and two minutes' rest between each set. After that, you'll do the stationary jumps that you did at the start again five good times. Then you'll take a 10-minute rest break and do both movements (stationary jump and four-step jump) again, five good times each. At the end of the data collection, I will give you written instructions about the two practice sessions that you will do on your own.

3. Follow-up visit one week later

The third lab visit will last approximately 45 minutes. It will be similar to the first part of the first data collection visit. You will change into shorts, socks, and sandals, warm-up and then have the silver balls and plastic shells attached to you. We will take a measurement of you standing still and then you will do the stationary jump five good times.

4. Final visit one week after follow-up visit

The fourth lab visit will last approximately 45 minutes. It will be similar to the follow-up visit. You will change into shorts, socks, and sandals, warm-up and then have the silver balls and plastic shells attached to you. We will take a measurement of you standing still and then you will do the stationary jump and four-step jump, five good times each.

Potential Risks

The potential risks associated with this study include trips and falls as you perform the jumping and cutting tasks. I will do my best to minimize these risks by explaining what will happen during each part of the study and letting you practice everything, you will also warm-up before starting the activities. You will be able to ask questions at any time during data collection if you are unsure about anything.

If you become injured during the data collection, standard first aid procedures would be carried out as needed. In the event of physical injury as a result of taking part in this study, the University of Tennessee does not automatically provide reimbursement for medical care or other compensation.

Benefits of Participation

While there are no immediate benefits to you following participation in this study, the results of the study will provide information about the effects of jump training on jump-landing technique. This information may be important in the development of programs aimed at reducing ACL injuries. In addition, you will receive compensation for your time of up to \$15 dollars if you attend all four laboratory visits.

Confidentiality

Your identity will be kept confidential by using code numbers to identify your information after data collection. These numbers will be used during all processing and analysis of the data and reports of the study and its results. As part of the initial screening process, you will be videotaped. The video image will be framed so that your face will not be included in the video. The video clips will be collected directly onto a personal computer. The video clips will not be identified by name, but by a subject number.

Contact Information

If you have any questions at any time about the study you can contact Jeremiah Tate. Questions about your rights as a participant can be addressed to Research Compliance Services in the Office of Research at (865) 974-3466.

Questions and/ or Withdrawal

You may ask questions and/ or withdraw your consent at any time and discontinue participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Consent

By signing, I am indicating that I understand the potential risks and benefits of participation in this study and that I am agreeing to participate in this study.

_____ Participant's Signature	_____ Date	_____ Subject #
_____ Investigator's Signature	_____ Date	

Appendix B. IRB Form for Experimental Group.

INFORMED CONSENT FORM The Performance and Learning Effects of Jump-Training on Jump Landing Technique in Female Recreational Athletes

Principal Investigator: Jeremiah Tate, PT, MS

Address: Dept of Exercise, Sport & Leisure Studies
University of Tennessee, 1914 Andy Holt Avenue, HPER 136
Knoxville, TN 37966

Phone: (865) 974-2091 (lab); (423) 883-5586 (mobile)

Purpose

You are invited to take part in a research study entitled “The Performance and Learning Effects of Jump-Training on Jump Landing Technique in Female Recreational Athletes”. This study aims to find out whether movement patterns in female athletes can be changed based on jump-training. This study involves four visits to our laboratory over a three-week duration. You will also be asked to complete two additional practice sessions lasting approximately 15 minutes each between the first and second laboratory visits.

You have been invited to take part in this study because you are a currently healthy recreational female athlete between the ages of 18-30. Also, you have not had any surgeries or recent injuries in the last six months that will affect your jumping and running ability. You should not participate in this study if you have a history of ACL injury or if you have ever participated in an ACL injury prevention program prior to this testing.

If you meet these criteria and agree to participate, we will measure your body mass index (a combination of height and weight) to make sure that it is below the limit of 30 for inclusion in our study. If you do not meet all of these criteria or choose not to participate in the study, your visit will end.

Laboratory Visits

1. Screening

If you are below the limit for body mass index, you will stay at the lab for 30 minutes for screening. The screening will determine if you are likely to benefit from our jump-training program. You will need to wear the sports bra, shorts, and tennis shoes that we asked you to bring with you. First, you will ride a stationary bike for five minutes and stretch your thigh and calf muscles to warm-up. I will help guide you through these stretches.

Next, I will measure how high you can jump using a Vertec jump measuring device. You will practice twice and then jump as high as you can three times. Next you will perform three jumps where you reach up and grab a basketball that is connected to a retractable string. The ball will be at 80% of your maximum jump height. Your body will be videotaped during these jumps (your face will not be recorded). I will review the video to see whether you may benefit from our jump-training. If you meet the screening criterion, then you will be scheduled to return to the lab in the near future for further data collection. If the video indicates that you would not benefit from our jump-training, then your visit will end.

2. First data collection visit

The second lab visit will last approximately two hours. You will change into a pair of shorts, socks, and sandals that we provide. You will then have small silver balls attached to your waist, hips, legs and feet using medical tape and plastic shells. These will not interfere with your ability to jump and run. The cameras in our lab record the position of these balls as you jump, run and cut in the laboratory space. We will take some measurements of you standing still first.

Next, you will perform five good attempts at the following sports skills: stationary jump and four-step jump. You will grab the hanging ball in both of the jumps. I will demonstrate each movement and you will be able to practice it until you feel comfortable with the task. Then you will perform the task for data collection. You will be able to rest as much as you need.

Next, you will do the jump-training. I will provide you with instructions on how to land and give you a demonstration. Then you will practice in front of a mirror. You will do three sets of jumps, with eight jumps in each set. You will take a 20 second break between each jump and two minutes' rest between each set. After that, you'll do the stationary jumps that you did at the start again five good times. Then you'll take a 10-minute rest break and do both movements (stationary jump and four-step jump) again, five good times each. At the end of the data collection, I will give you written instructions about the two practice sessions that you will do on your own.

3. Follow-up visit one week later

The third lab visit will last approximately 45 minutes. It will be similar to the first part of the first data collection visit. You will change into shorts, socks, and sandals, warm-up and then have the silver balls and plastic shells attached to you. We will take a measurement of you standing still and then you will do the stationary jump five good times.

4. Final visit one week after follow-up visit

The fourth lab visit will last approximately 45 minutes. It will be similar to the follow-up visit. You will change into shorts, socks, and sandals, warm-up and then have the silver balls and plastic shells attached to you. We will take a measurement of you standing still and then you will do the stationary jump and four-step jump, five good times each.

Potential Risks

The potential risks associated with this study include trips and falls as you perform the jumping and cutting tasks. I will do my best to minimize these risks by explaining what will happen during each part of the study and letting you practice everything, you will also warm-up before starting the activities. You will be able to ask questions at any time during data collection if you are unsure about anything.

If you become injured during the data collection, standard first aid procedures would be carried out as needed. In the event of physical injury as a result of taking part in this study, the University of Tennessee does not automatically provide reimbursement for medical care or other compensation.

Benefits of Participation

While there are no immediate benefits to you following participation in this study, the

results of the study will provide information about the effects of jump training on jump-landing technique. This information may be important in the development of programs aimed at reducing ACL injuries. In addition, you will receive compensation for your time of up to \$15 dollars if you attend all four laboratory visits.

Confidentiality

Your identity will be kept confidential by using code numbers to identify your information after data collection. These numbers will be used during all processing and analysis of the data and reports of the study and its results. As part of the initial screening process, you will be videotaped. The video image will be framed so that your face will not be included in the video. The video clips will be collected directly onto a personal computer. The video clips will not be identified by name, but by a subject number.

Contact Information

If you have any questions at any time about the study you can contact Jeremiah Tate. Questions about your rights as a participant can be addressed to Research Compliance Services in the Office of Research at (865) 974-3466.

Questions and/ or Withdrawal

You may ask questions and/ or withdraw your consent at any time and discontinue participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Consent

By signing, I am indicating that I understand the potential risks and benefits of participation in this study and that I am agreeing to participate in this study.

_____	_____	_____
Participant's Signature	Date	Subject #
_____	_____	
Investigator's Signature	Date	

Appendix C. Activity Questionnaire

Activity and Injury Questionnaire: “The Performance and Learning Effects of Jump-Training Instructions on Jump Landing Technique in Female Recreational Athletes”

Subject ID#: _____ Date: _____

Age: _____ Height: _____ Weight _____

1. Have you had an injury to either leg in the past 6 months that has limited your normal activities for more than 2 weeks? Yes or No
2. Have you ever ruptured or torn completely any ligaments in your feet, ankles, knees, or hips? Yes or No
3. Have you ever had surgery on either one of your legs? Yes or No
4. Are you currently participating in regular exercise? Yes or No
5. If yes, how many hours do you exercise per week? _____
6. How many of these hours are devoted to jumping and landing activities? _____
7. What types of jumping and landing activities have you been regularly engaging in at least once a month (e.g., basketball, volleyball, etc.)?

8. Prior to the last six months did you have any experience in jumping and landing activities? Yes or No

9. If yes, what activities were they? _____

10. How many years have you engaged in those activities?

11. Over those years, approximately how many months/year? _____
days/week? _____, hours/session? _____

Appendix D. Physical Activity Readiness Questionnaire

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
☐	☐	1. Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?
☐	☐	2. Do you feel pain in your chest when you do physical activity?
☐	☐	3. In the past month, have you had chest pain when you were not doing physical activity?
☐	☐	4. Do you lose your balance because of dizziness or do you ever lose consciousness?
☐	☐	5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?
☐	☐	6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
☐	☐	7. Do you know of <u>any other reason</u> why you should not do physical activity?

If
you
answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or
- if you are or may be pregnant — talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME _____

SIGNATURE _____

DATE _____

SIGNATURE OF PARENT _____
or GUARDIAN (for participants under the age of majority)

WITNESS _____

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.



© Canadian Society for Exercise Physiology

Supported by:



Health
Canada

Santé
Canada

continued on other side...

Appendix E. Exploder System



Appendix F. Marker set



a) Anterior view



b) Posterior view

Appendix G. Countermovement-Jump Task



Appendix H. Stop-Jump Task



Appendix I. Diagram of overall data collection process.

		Phase One		Phase Two	
Time	Baseline	Immediate Retention	Delayed Retention	Retention 1	Retention 2
Day	Day1	Day1	Day1	1 week later	2 weeks later
Condition (s)	CMJ	CMJ	CMJ	CMJ	CMJ
Condition (s)	SJ		SJ		SJ

Appendix J. Jump Instructions for Experimental Group.

Reminder: You are part of a study analyzing the effects of different types of jump training. Please do not share any specific information about this training program with other study participants (or potential participants).

Instructions: During the following week, you will practice jump-landings on your own time. The first practice session will occur two days after your visit to the lab, and the second practice session will occur four days later.

Practice Schedule

Day	1	2	3	4	5	6	7	8
Date								
	Lab		Session One		Session Two			Lab*

*You will return to the lab 1 week following your initial lab visit.

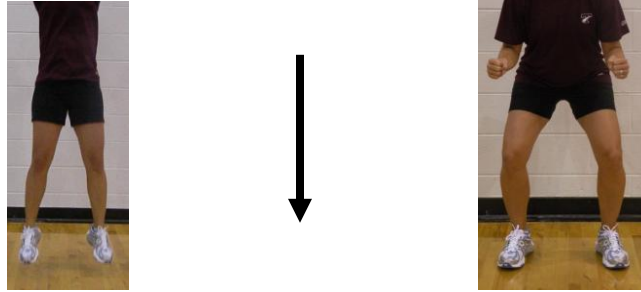
Warm-up: Prior to practicing jump-landings, you will perform a short warm-up to minimize your risk of injury. This warm-up should include a 3-5 minute brisk walk followed by stretching of the quadriceps (front of the thigh), hamstrings (back of the thigh), and calf muscles as performed in the in the lab prior to testing.

Jumping-landing instructions: During each of your practice sessions, you will perform 3 sets of 5 countermovement jumps. The countermovement jump is the same jump technique that you performed during the screening session in the lab.

Session One (Day 3)

During your **first** practice session, you will perform the first two sets of jumps in front of a full-length mirror. The room in which you practice must have adequate ceiling height for you to jump as high as possible without contacting the ceiling. As you complete these two sets, **focus on the image in the mirror**, and try to minimize any inward movement of the knees towards one another. Concentrate on keeping the knees directly above the feet. You will perform the third set of jumps **without** using the mirror. We want you to continue practice landing using the same technique.

Give yourself a 20-second rest between jumps, and a 2-minute rest between sets.



Session Two (Day 5)

During your **second** practice session, you will perform the first set of jumps in front of a full-length mirror. As you complete this first set, **focus on the image in the mirror**, and try to minimize any inward movement of the knees towards one another. Concentrate on keeping the knees directly above the feet. You will perform the second and third set of jumps **without** using the mirror. We want you to continue practice landing using the same technique.

Give yourself a 20-second rest between jumps, and a 2-minute rest between sets.

Training Log

	Session One	Session Two
Set 1 (5 jumps)	Initials*:	Initials*:
Set 2 (5 jumps)	Initials*:	Initials*: (No mirror)
Set 3 (5 jumps)	Initials*: (No mirror)	Initials*: (No mirror)

*Indicate your completion of each set with your initials.

Bring this completed form with you to your next laboratory session.

Appendix K. Jump Instructions for Control Group.

Reminder: You are part of a study analyzing the effects of different types of jump training. Please do not share any specific information about this training program with other study participants (or potential participants).

Instructions: During the following week, you will practice jumping on your own time. The first practice session will occur two days after your visit to the lab, and the second practice session will occur four days later.

Practice Schedule

Day	1	2	3	4	5	6	7	8
Date								
	Lab		Session One		Session Two			Lab*

*You will return to the lab 1 week following your initial lab visit.

Warm-up: Prior to practicing jump-landings, you will perform a short warm-up to minimize your risk of injury. This warm-up should include a 3-5 minute brisk walk followed by stretching of the quadriceps (front of the thigh), hamstrings (back of the thigh), and calf muscles as performed in the in the lab prior to testing.

Jumping-landing instructions: During each practice session, you will perform 3 sets of 5 countermovement jumps. The countermovement jump is the same jump technique that you performed during the screening session in the lab.

Practice Sessions (Days 3 & 5)

During **each** practice session, you will perform three sets of 5 countermovement jumps. The room in which you practice must have adequate ceiling height for you to jump as high as possible without contacting the ceiling.

Give yourself a 20-second rest between jumps, and a 2-minute rest between sets.

Training Log

	Session One	Session Two
Set 1 (5 jumps)	Initials*:	Initials*:
Set 2 (5 jumps)	Initials*:	Initials*:
Set 3 (5 jumps)	Initials*:	Initials*:

*Indicate your completion of each set with your initials.

Bring this completed form with you to your next laboratory session.

Appendix L. Demographic data values for each participant that completed the study protocol. (n=26)

Subject #	Age (yrs)	Ht (m)	Wt (kg)	BMI (kg/m2)	Max Vert Jump Ht (m)	Valgus Limb (side)
1	23	1.47	53.2	24.7	0.27	Bilateral
2	20	1.61	58.6	22.5	0.35	Bilateral
3	19	1.71	64.5	22.1	0.31	Right
4	19	1.70	55.5	19.1	0.39	Left
5	20	1.70	65.9	22.9	0.47	Bilateral
6	18	1.73	85.9	28.8	0.50	Right
7	21	1.64	58.0	21.6	0.35	Right
9	18	1.68	66.4	23.4	0.52	Right
11	18	1.66	56.8	20.5	0.40	Bilateral
12	22	1.65	72.7	26.7	0.29	Bilateral
13	22	1.56	50.0	20.7	0.36	Left
14	21	1.71	71.8	24.4	0.36	Right
15	21	1.59	55.9	22.2	0.36	Left
16	19	1.66	62.3	22.7	0.29	Right
17	22	1.64	58.2	21.7	0.48	Right
18	19	1.63	62.3	23.6	0.36	Right
19	22	1.70	61.4	21.2	0.29	Bilateral
20	25	1.68	65.9	23.3	0.28	Right
21	25	1.82	86.4	26.2	0.34	Right
22	20	1.78	70.9	22.4	0.34	Right
23	26	1.55	52.7	22.0	0.37	Right
24	21	1.60	60.0	23.4	0.33	Bilateral
26	23	1.73	67.7	22.7	0.39	Right
27	22	1.68	63.6	22.5	0.28	Right
28	23	1.69	63.2	22.1	0.35	Right
29	21	1.69	75.9	26.6	0.41	Right
Mean	21.2	1.66	64.1	23.1	0.36	n/a
SD	2.2	0.07	9.1	2.1	0.07	n/a

Note: Subjects' # 8,10,and 25 did not complete study protocol due to injury.

Appendix M. Individual data values for dependent variables.

Peak internal adduction moment (Nm/kg) for countermovement jump, phase one.

a) Control Group

Subject	Baseline	Immediate Retention	Delayed Retention
2	0.66	0.57	0.79
5	0.94	0.73	0.74
6	0.44	0.90	0.72
9	0.55	0.66	0.80
11	0.43	0.57	0.56
13	0.63	0.62	0.58
16	0.26	0.21	0.23
17	0.34	0.32	0.23
18	0.65	0.50	0.62
20	0.28	0.50	0.29
21	0.17	0.16	0.15
24	0.27	0.53	0.45
29	0.06	0.12	0.22
Mean	0.44	0.49	0.49
SD	0.24	0.23	0.24

b) Experimental Group

Subject	Baseline	Immediate Retention	Delayed Retention
1	0.45	0.37	0.49
3	0.29	0.27	0.32
4	0.86	0.61	0.58
7	0.42	0.28	0.60
12	0.34	0.31	0.32
14	0.37	0.33	0.41
15	0.75	0.77	0.89
19	0.98	0.84	0.65
22	0.30	0.14	0.42
23	0.60	0.28	0.41
26	0.72	0.46	0.40
27	0.56	0.54	0.70
28	0.50	0.54	0.84
Mean	0.55	0.44	0.54
SD	0.22	0.21	0.19

Peak abduction angle (°) for countermovement jump, phase one.

a) Control Group

Subject	Baseline	Immediate Retention	Delayed Retention
2	-6.6	-5.0	-6.4
5	-7.9	-8.9	-5.8
6	-11.7	-21.4	-19.6
9	-9.1	-11.0	-14.7
11	-9.1	-12.4	-11.8
13	-13.0	-12.7	-12.4
16	-6.9	-5.5	-4.9
17	-5.6	-4.0	-6.0
18	-3.7	-5.5	-8.0
20	-6.8	-11.0	-6.5
21	-7.5	-8.2	-8.2
24	-10.4	-10.4	-12.1
29	-4.5	-4.6	-8.2
Mean	-7.9	-9.3	-9.6
SD	2.7	4.8	4.3

b) Experimental Group

Subject	Baseline	Immediate Retention	Delayed Retention
1	-14.0	-13.7	-15.7
3	-5.6	-7.5	-7.7
4	-14.0	-16.7	-15.7
7	-9.8	-7.6	-8.6
12	-11.1	-10.6	-10.4
14	-8.2	-9.0	-11.0
15	-11.2	-12.4	-13.4
19	-17.4	-16.3	-14.0
22	-5.2	-4.1	-5.7
23	-6.0	-5.6	-6.7
26	-7.3	-6.8	-7.4
27	-15.8	-18.7	-16.6
28	-6.3	-5.2	-9.5
Mean	-10.1	-10.3	-11.0
SD	4.1	4.8	3.8

Peak internal extension moment (Nm/kg) for countermovement jump, phase one.

a) Control Group

Subject	Baseline	Immediate Retention	Delayed Retention
2	2.32	2.23	2.27
5	2.35	1.76	2.16
6	2.29	2.43	2.28
9	2.65	2.28	2.06
11	2.83	2.51	2.69
13	1.74	1.82	1.71
16	1.25	1.54	1.87
17	2.87	2.85	2.88
18	2.01	2.28	2.14
20	2.78	2.37	2.70
21	1.84	1.89	1.78
24	2.03	2.33	2.04
29	2.12	1.81	2.10
Mean	2.24	2.16	2.20
SD	0.48	0.37	0.36

b) Experimental Group

Subject	Baseline	Immediate Retention	Delayed Retention
1	1.50	1.37	1.35
3	3.00	2.77	2.97
4	3.29	2.01	2.09
7	1.64	1.57	1.54
12	2.04	2.06	2.05
14	3.21	2.98	3.05
15	2.31	1.76	1.73
19	1.77	1.76	1.68
22	2.51	2.29	2.25
23	1.81	1.98	1.87
26	2.68	2.24	2.27
27	1.75	1.63	1.67
28	2.07	2.34	2.97
Mean	2.28	2.06	2.12
SD	0.61	0.47	0.57

Knee excursion (°) for countermovement jump, phase one.

a) Control Group

Subject	Baseline	Immediate Retention	Delayed Retention
2	63.5	65.0	58.6
5	33.6	34.8	36.6
6	68.6	67.8	66.1
9	56.6	63.0	53.2
11	66.7	65.6	62.2
13	48.5	56.2	64.4
16	59.5	53.8	58.1
17	67.8	68.1	69.5
18	65.4	69.8	59.4
20	60.3	57.7	57.9
21	70.1	71.8	69.1
24	36.9	35.6	41.2
29	71.1	75.9	75.7
Mean	59.1	60.4	59.4
SD	12.3	12.8	10.9

b) Experimental Group

Subject	Baseline	Immediate Retention	Delayed Retention
1	93.0	103.2	108.4
3	57.4	58.6	56.3
4	82.3	101.2	108.3
7	89.1	97.5	97.0
12	64.2	66.1	65.4
14	57.9	68.6	66.5
15	68.5	63.1	62.2
19	55.9	63.0	68.9
22	49.2	67.2	70.6
23	63.8	77.7	74.4
26	60.6	70.7	72.4
27	55.1	62.4	61.8
28	63.1	80.6	74.6
Mean	66.2	75.4	75.9
SD	13.6	15.7	17.4

Peak vertical ground reaction force (%BW) for countermovement jump, phase one.

a) Control Group

Subject	Baseline	Immediate Retention	Delayed Retention
2	1.54	1.72	1.85
5	2.18	2.09	2.15
6	1.61	1.89	1.71
9	1.94	1.63	1.68
11	2.33	2.04	2.24
13	1.42	1.59	1.27
16	0.95	1.14	1.57
17	1.89	2.07	1.89
18	2.34	2.04	1.99
20	1.80	1.70	1.76
21	1.28	1.30	1.26
24	1.60	1.55	1.39
29	1.62	1.12	1.57
Mean	1.73	1.68	1.72
SD	0.41	0.34	0.31

b) Experimental Group

Subject	Baseline	Immediate Retention	Delayed Retention
1	1.25	1.11	1.08
3	2.29	2.29	2.26
4	2.40	1.38	1.35
7	1.18	1.05	1.01
12	1.78	1.80	1.65
14	2.52	2.33	2.44
15	2.01	1.63	1.69
19	1.57	1.35	1.40
22	1.83	1.66	1.58
23	1.53	1.53	1.36
26	1.75	1.57	1.49
27	1.67	1.39	1.61
28	1.71	1.73	2.12
Mean	1.81	1.60	1.62
SD	0.41	0.39	0.43

Peak internal adduction moment (Nm/kg) for stop-jump task, phase one.

a) Control Group

Subject	Baseline	Transfer
2	0.51	0.35
5	0.61	0.99
6	0.91	0.91
9	0.83	1.04
11	0.74	0.64
13	0.62	0.65
16	0.69	0.59
17	0.86	0.72
18	0.89	0.91
20	0.54	0.68
21	0.51	0.40
24	1.25	1.04
29	0.20	0.40
Mean	0.70	0.72
SD	0.26	0.25

b) Experimental Group

Subject	Baseline	Transfer
1	0.47	0.52
3	0.27	0.22
4	1.65	1.36
7	0.58	0.47
12	0.73	0.72
14	1.21	1.31
15	1.34	1.23
19	0.68	0.66
22	0.34	0.13
23	0.60	0.37
26	1.09	1.04
27	0.73	0.95
28	1.14	1.00
Mean	0.83	0.77
SD	0.42	0.41

Peak abduction angle (°) for stop-jump task, phase one.

a) Control Group

Subject	Baseline	Transfer
2	-6.2	-8.3
5	-7.0	-12.2
6	-24.0	-28.0
9	-19.5	-21.5
11	-14.5	-14.7
13	-15.3	-18.2
16	-11.3	-11.6
17	-13.4	-10.6
18	-13.9	-15.4
20	-11.6	-15.6
21	-11.1	-12.3
24	-23.7	-21.8
29	-2.1	-6.2
Mean	-13.4	-15.1
SD	6.4	6.0

b) Experimental Group

Subject	Baseline	Transfer
1	-10.3	-13.1
3	-7.6	-6.7
4	-21.5	-20.8
7	-14.5	-12.5
12	-17.3	-20.2
14	-17.2	-17.1
15	-17.1	-17.9
19	-13.9	-13.4
22	-6.6	-2.1
23	-5.3	-6.3
26	-18.8	-18.5
27	-15.5	-15.1
28	-6.2	-12.2
Mean	-13.2	-13.5
SD	5.4	5.7

Peak abduction angle (°) for countermovement jump, phase one.

a) Control Group

Subject	Baseline	Retention 1	Retention 2
2	-6.6	-5.3	-8.0
5	-7.9	-6.8	-5.7
6	-11.7	-12.5	-17.2
9	-9.1	-8.8	-12.9
11	-9.1	-15.9	-17.0
13	-13.0	-13.5	-15.5
16	-6.9	-4.5	-9.6
17	-5.6	-2.8	-7.1
18	-3.7	-5.0	-3.9
20	-6.8	-5.1	-6.3
21	-7.5	-11.0	-10.7
24	-10.4	-6.7	-9.4
29	-4.5	-7.2	-7.67
Mean	-7.9	-8.1	-10.1
SD	2.7	4.0	4.4

b) Experimental Group

Subject	Baseline	Retention 1	Retention 2
1	-14.0	-13.9	-10.3
3	-5.6	-7.9	-13.3
4	-14.0	-13.1	-10.2
7	-9.8	-11.1	-8.5
12	-11.1	-9.8	-13.7
14	-8.2	-10.9	-12.7
15	-11.2	-12.2	-17.2
19	-17.4	-8.2	-10.7
22	-5.2	-10.3	-6.4
23	-6.0	-8.9	-5.9
26	-7.3	-7.6	-8.9
27	-15.8	-12.6	-14.5
28	-6.3	-6.8	-2.0
Mean	-10.1	-10.2	-10.3
SD	4.1	2.3	4.1

Peak internal extension moment (Nm/kg) for stop-jump task, phase one.

a) Control Group

Subject	Baseline	Transfer
2	2.56	2.36
5	2.40	2.69
6	2.36	2.20
9	3.26	3.17
11	2.53	2.32
13	1.78	1.85
16	2.44	2.16
17	4.16	3.93
18	3.02	2.80
20	3.52	3.33
21	2.32	2.14
24	2.42	2.47
29	1.91	1.96
Mean	2.67	2.57
SD	0.66	0.60

b) Experimental Group

Subject	Baseline	Transfer
1	1.83	1.87
3	2.98	2.67
4	2.44	2.44
7	2.46	2.27
12	2.43	2.17
14	3.04	3.04
15	2.26	2.06
19	3.79	3.46
22	2.31	2.11
23	2.43	2.49
26	3.32	3.13
27	2.69	2.53
28	2.25	2.21
Mean	2.63	2.50
SD	0.52	0.47

Knee excursion (°) for stop-jump task, phase one.

a) Control Group

Subject	Baseline	Transfer
2	57.6	58.4
5	68.0	61.6
6	63.6	63.4
9	52.5	45.0
11	41.5	31.3
13	57.1	57.3
16	53.5	57.9
17	43.3	49.2
18	33.8	30.3
20	50.9	51.5
21	38.8	39.5
24	41.5	38.0
29	55.8	60.1
Mean	50.6	49.5
SD	10.2	11.6

b) Experimental Group

Subject	Baseline	Transfer
1	53.5	56.9
3	45.1	48.8
4	30.0	33.7
7	60.1	59.4
12	55.8	62.5
14	58.1	61.7
15	41.3	31.8
19	41.1	43.2
22	51.9	57.2
23	44.6	45.7
26	44.9	45.6
27	42.9	47.8
28	28.1	25.2
Mean	45.9	47.7
SD	9.9	11.9

Peak vertical ground reaction force (%BW) for stop-jump task, phase one

a) Control Group

Subject	Baseline	Transfer
2	1.66	1.62
5	1.89	1.85
6	1.40	1.46
9	1.98	2.14
11	1.44	1.51
13	1.58	1.45
16	2.32	1.65
17	2.97	3.11
18	2.74	3.02
20	1.57	1.55
21	1.33	1.33
24	1.66	2.03
29	1.61	1.71
Mean	1.86	1.88
SD	0.52	0.58

b) Experimental Group

Subject	Baseline	Transfer
1	1.80	2.14
3	2.17	2.03
4	2.00	1.75
7	1.47	1.41
12	3.00	2.41
14	4.10	4.09
15	1.91	1.66
19	2.00	1.86
22	1.31	1.11
23	2.01	2.01
26	1.75	1.84
27	2.43	2.94
28	1.99	2.35
Mean	2.15	2.12
SD	0.72	0.75

Peak internal adduction moment (Nm/kg) for countermovement jump, phase two.

a) Control Group

Subject	Baseline	Retention 1	Retention 2
2	0.66	0.83	0.68
5	0.94	0.64	0.68
6	0.44	0.56	0.75
9	0.55	0.96	0.84
11	0.43	0.66	0.80
13	0.63	0.67	0.75
16	0.26	0.34	0.39
17	0.34	0.21	0.38
18	0.65	0.51	0.48
20	0.28	0.29	0.39
21	0.17	0.18	0.26
24	0.27	0.33	0.24
29	0.06	0.23	0.61
Mean	0.44	0.49	0.56
SD	0.24	0.25	0.21

b) Experimental Group

Subject	Baseline	Retention 1	Retention 2
1	0.45	0.31	0.27
3	0.29	0.43	0.54
4	0.86	0.50	0.50
7	0.42	0.47	0.32
12	0.34	0.30	0.52
14	0.37	0.50	0.42
15	0.75	0.88	0.81
19	0.98	0.71	0.77
22	0.30	0.24	0.29
23	0.60	0.58	0.72
26	0.72	0.29	0.53
27	0.56	0.52	0.70
28	0.50	0.57	0.54
Mean	0.55	0.48	0.53
SD	0.22	0.18	0.18

Peak abduction angle (°) for countermovement jump, phase two.

a) Control Group

Subject	Baseline	Retention 1	Retention 2
2	-6.6	-5.3	-8.0
5	-7.9	-6.8	-5.7
6	-11.7	-12.5	-17.2
9	-9.1	-8.8	-12.9
11	-9.1	-15.9	-17.0
13	-13.0	-13.5	-15.5
16	-6.9	-4.5	-9.6
17	-5.6	-2.8	-7.1
18	-3.7	-5.0	-3.9
20	-6.8	-5.1	-6.3
21	-7.5	-11.0	-10.7
24	-10.4	-6.7	-9.4
29	-4.5	-7.2	-7.67
Mean	-7.9	-8.1	-10.1
SD	2.7	4.0	4.4

b) Experimental Group

Subject	Baseline	Retention 1	Retention 2
1	-14.0	-13.9	-10.3
3	-5.6	-7.9	-13.3
4	-14.0	-13.1	-10.2
7	-9.8	-11.1	-8.5
12	-11.1	-9.8	-13.7
14	-8.2	-10.9	-12.7
15	-11.2	-12.2	-17.2
19	-17.4	-8.2	-10.7
22	-5.2	-10.3	-6.4
23	-6.0	-8.9	-5.9
26	-7.3	-7.6	-8.9
27	-15.8	-12.6	-14.5
28	-6.3	-6.8	-2.0
Mean	-10.1	-10.2	-10.3
SD	4.1	2.3	4.1

Peak internal extension moment (Nm/kg) for countermovement jump, phase two.

a) Control Group

Subject	Baseline	Retention 1	Retention 2
2	2.32	2.61	2.55
5	2.35	2.32	2.54
6	2.29	2.44	2.30
9	2.65	2.69	2.43
11	2.83	2.64	2.28
13	1.74	1.61	1.81
16	1.25	1.41	1.75
17	2.87	3.12	2.65
18	2.01	2.32	2.64
20	2.78	2.43	2.61
21	1.84	1.57	1.54
24	2.03	2.22	1.87
29	2.12	2.33	2.22
Mean	2.24	2.29	2.25
SD	0.48	0.49	0.38

b) Experimental Group

Subject	Baseline	Retention 1	Retention 2
1	1.50	1.34	1.44
3	3.00	2.86	2.68
4	3.29	1.82	2.19
7	1.64	1.83	1.77
12	2.04	1.85	1.82
14	3.21	2.66	2.33
15	2.31	2.25	1.85
19	1.77	2.02	2.04
22	2.51	2.13	2.37
23	1.81	1.80	2.25
26	2.68	2.24	2.36
27	1.75	1.85	2.01
28	2.07	2.37	2.82
Mean	2.28	2.08	2.15
SD	0.61	0.40	0.38

Knee excursion (°) for countermovement jump, phase two.

a) Control Group

Subject	Baseline	Retention 1	Retention 2
2	63.5	54.5	55.8
5	33.6	33.1	34.4
6	68.6	56.5	65.1
9	56.6	53.1	60.5
11	66.7	62.4	62.1
13	48.5	64.2	72.4
16	59.5	54.8	55.9
17	67.8	69.7	60.6
18	65.4	60.5	51.6
20	60.3	49.2	62.2
21	70.1	66.0	61.2
24	36.9	38.2	44.5
29	71.1	66.1	71.7
Mean	59.1	56.0	58.3
SD	12.3	10.9	10.4

b) Experimental Group

Subject	Baseline	Retention 1	Retention 2
1	93.0	99.0	110.7
3	57.4	60.1	63.4
4	82.3	102.9	98.2
7	89.1	83.2	89.4
12	64.2	56.1	63.3
14	57.9	62.2	68.3
15	68.5	56.2	55.6
19	55.9	55.9	48.4
22	49.2	57.4	67.3
23	63.8	76.3	78.6
26	60.6	71.6	70.4
27	55.1	57.7	48.6
28	63.1	67.2	69.4
Mean	66.2	69.7	71.7
SD	13.6	16.3	18.5

Peak vertical ground reaction force (%BW) for countermovement jump, phase two.

a) Control Group

Subject	Baseline	Retention 1	Retention 2
2	1.54	2.17	2.08
5	2.18	2.36	2.32
6	1.61	1.67	1.49
9	1.94	2.40	2.02
11	2.33	2.05	1.89
13	1.42	1.35	1.48
16	0.95	1.06	1.22
17	1.89	2.06	2.01
18	2.34	2.14	2.37
20	1.80	1.66	1.59
21	1.28	1.30	1.16
24	1.60	1.63	1.63
29	1.62	1.75	1.596
Mean	1.73	1.81	1.76
SD	0.41	0.42	0.39

b) Experimental Group

Subject	Baseline	Retention 1	Retention 2
1	1.25	1.04	1.00
3	2.29	2.30	2.39
4	2.40	1.26	1.53
7	1.18	1.11	1.21
12	1.78	1.92	1.94
14	2.52	2.32	2.26
15	2.01	1.80	1.63
19	1.57	1.55	1.57
22	1.83	1.48	1.73
23	1.53	1.35	1.57
26	1.75	1.71	1.62
27	1.67	1.67	1.94
28	1.71	1.76	1.95
Mean	1.81	1.64	1.72
SD	0.41	0.40	0.38

Peak internal adduction moment (Nm/kg) for stop-jump task, phase two.

a) Control Group

Subject	Baseline	Transfer
2	0.51	0.54
5	0.61	1.03
6	0.91	1.11
9	0.83	1.45
11	0.74	0.84
13	0.62	0.82
16	0.69	0.78
17	0.86	0.66
18	0.89	0.83
20	0.54	0.10
21	0.51	0.57
24	1.25	1.01
29	0.20	0.30
Mean	0.70	0.77
SD	0.26	0.35

b) Experimental Group

Subject	Baseline	Transfer
1	0.47	0.65
3	0.27	0.48
4	1.65	0.99
7	0.58	0.84
12	0.73	0.81
14	1.21	1.62
15	1.34	1.04
19	0.68	0.63
22	0.34	0.20
23	0.60	0.31
26	1.09	1.41
27	0.73	0.98
28	1.14	1.05
Mean	0.83	0.85
SD	0.42	0.40

Peak abduction angle (°) for stop-jump task, phase two.

a) Control Group

Subject	Baseline	Transfer
2	-6.2	-12.0
5	-7.0	-10.9
6	-24.0	-27.2
9	-19.5	-24.6
11	-14.5	-18.8
13	-15.3	-19.1
16	-11.3	-11.0
17	-13.4	-12.8
18	-13.9	-12.1
20	-11.6	-3.3
21	-11.1	-18.4
24	-23.7	-18.3
29	-2.1	-4.8
Mean	-13.4	-14.9
SD	6.4	7.0

b) Experimental Group

Subject	Baseline	Transfer
1	-10.3	-14.9
3	-7.6	-13.3
4	-21.5	-16.8
7	-14.5	-21.8
12	-17.3	-16.8
14	-17.2	-18.4
15	-17.1	-16.8
19	-13.9	-11.5
22	-6.6	-4.6
23	-5.3	-4.2
26	-18.8	-22.3
27	-15.5	-15.4
28	-6.2	-3.0
Mean	-13.2	-13.8
SD	5.4	6.4

Peak internal extension moment (Nm/kg) for stop-jump task, phase two.

a) Control Group

Subject	Baseline	Transfer
2	2.56	2.48
5	2.40	3.31
6	2.36	2.69
9	3.26	3.45
11	2.53	2.41
13	1.78	2.13
16	2.44	2.38
17	4.16	4.18
18	3.02	3.11
20	3.52	3.50
21	2.32	2.26
24	2.42	2.56
29	1.91	2.05
Mean	2.67	2.81
SD	0.66	0.65

b) Experimental Group

Subject	Baseline	Transfer
1	1.83	1.95
3	2.98	2.70
4	2.44	2.43
7	2.46	2.28
12	2.43	2.50
14	3.04	2.93
15	2.26	2.56
19	3.79	3.55
22	2.31	2.12
23	2.43	2.61
26	3.32	3.11
27	2.69	3.12
28	2.25	2.26
Mean	2.63	2.63
SD	0.52	0.45

Knee excursion (°) for stop-jump task, phase two.

a) Control Group

Subject	Baseline	Transfer
2	57.6	59.1
5	68.0	56.0
6	63.6	60.4
9	52.5	46.5
11	41.5	34.3
13	57.1	50.1
16	53.5	56.2
17	43.3	44.1
18	33.8	32.6
20	50.9	52.8
21	38.8	47.1
24	41.5	38.9
29	55.8	68.6
Mean	50.6	49.8
SD	10.2	10.6

b) Experimental Group

Subject	Baseline	Transfer
1	53.5	51.9
3	45.1	47.2
4	30.0	38.4
7	60.1	56.5
12	55.8	58.3
14	58.1	52.5
15	41.3	34.4
19	41.1	36.9
22	51.9	57.9
23	44.6	43.6
26	44.9	38.8
27	42.9	38.5
28	28.1	29.0
Mean	45.9	44.9
SD	9.9	9.8

Peak vertical ground reaction force (%BW) for stop-jump task, phase two.

a) Control Group

Subject	Baseline	Transfer
2	1.66	1.47
5	1.89	2.42
6	1.40	1.58
9	1.98	2.25
11	1.44	1.57
13	1.58	1.63
16	2.32	2.14
17	2.97	3.01
18	2.74	3.17
20	1.57	1.64
21	1.33	1.39
24	1.66	1.82
29	1.61	1.24
Mean	1.86	1.95
SD	0.52	0.61

b) Experimental Group

Subject	Baseline	Transfer
1	1.80	2.49
3	2.17	1.82
4	2.00	1.47
7	1.47	1.58
12	3.00	2.38
14	4.10	3.94
15	1.91	1.64
19	2.00	2.26
22	1.31	1.15
23	2.01	2.03
26	1.75	1.96
27	2.43	3.13
28	1.99	2.15
Mean	2.15	2.15
SD	0.72	0.74

Appendix N. ANOVA Tables: Countermovement Jump, Phase One.

Peak internal knee adduction moment

Effect	F	P-value
Group	0.22	.6430
Time	1.27	.2906
Group*Time	3.50	.0381*

* p-value < 0.05

Peak knee abduction angle

Effect	F	P-value
Group	1.02	.3219
Time	3.64	.0339*
Group*Time	0.88	.4221

* p-value < 0.05

Peak knee abduction angle

Paired Contrasts	T	P value
Baseline vs. Retention 1	1.66	.1031
Baseline vs. Retention 2	2.67	.0103*
Retention 1 vs. Retention 2	1.01	.3183

*p-value < 0.05

Peak internal knee extension moment

Effect	F	P-value
Group	0.09	.7697
Time	2.81	.0703
Group*Time	0.79	.4611

Peak internal knee extension moment

Paired Contrasts	T	P value
Control Baseline vs. Experimental Baseline	-1.29	.2074
Control Baseline vs. Control Retention 1	-1.25	.2181
Control Baseline vs. Control Retention 2	-1.23	.2245
Control Retention 1 vs. Control Retention 2	0.02	.9860
Experimental Baseline vs. Experimental Retention 1	2.46	.0175*
Experimental Baseline vs. Experimental Retention 2	0.19	.8475
Experimental Retention 1 vs. Experimental Retention 2	-2.27	.0279*

Knee excursion

Effect	F	P-value
Group	5.90	0.0230*
Time	12.35	< 0.0001*
Group*Time	9.12	0.0004*

* p-value < 0.05

Knee Excursion

Paired Contrasts	T	P value
Control Baseline vs. Experimental Baseline	-1.29	.2087
Control Baseline vs. Control Retention 1	-0.75	.4550
Control Baseline vs. Control Retention 2	-0.16	.8769
Control Follow-up 1 vs. Con Retention 2	0.60	.9907
Experimental Baseline vs. Experimental Retention 1	-5.47	<.0001*
Experimental Baseline vs. Experimental Retention 2	-5.78	<.0001*
Experimental Retention 1 vs. Experimental Retention 2	-0.31	.7541

*p-value < 0.05

Peak Vertical Ground Reaction Force

Effect	F	P-value
Group	0.06	.8040
Time	3.74	.0310*
Group*Time	1.95	.1537

* p-value < 0.05

Peak vertical ground reaction force

Pairwise Contrasts	T	P value
Baseline vs. Retention 1	2.59	.0128*
Baseline vs. Retention 2	2.06	.0448*
Retention 1 vs. Retention 2	-0.53	.6008

*p-value < 0.05

Appendix O. ANOVA Tables: Stop-jump Task, Phase One.

Approach speed

Effect	F	P-value
Group	0.71	.4082
Time	2.21	.1503
Group*Time	0.17	.6834

Peak internal knee adduction moment

Effect	F	P-value
Group	0.47	.4998
Time	0.73	.4023
Group*Time	1.56	.2241

Peak knee abduction angle (°) for stop-jump task, phase one.

Effect	F	P-value
Group	0.14	.7079
Time	4.56	.0432*
Group*Time	2.20	.1509

* = $p < 0.05$

Peak internal knee extension moment

Effect	F	P-value
Group	0.06	.8121
Time	16.11	.0005*
Group*Time	0.39	.5375

* = $p < 0.05$

Knee excursion

Effect	F	P-value
Group	0.60	.4461
Time	0.11	.7438
Group*Time	2.46	.1301

Peak vertical ground reaction force

Effect	F	P-value
Group	1.16	.2913
Time	0.00	.9661
Group*Time	0.20	.6613

Appendix P. ANOVA Tables: Countermovement Jump, Phase Two.

Peak internal knee adduction moment

Effect	F	P-value
Group	0.12	0.7270
Time	1.68	0.1967
Group*Time	2.37	0.1039

Peak knee abduction angle

Effect	F	P-value
Group	1.58	.2210
Time	1.99	.1478
Group*Time	1.53	.2271

Peak internal knee extension moment

Effect	F	P-value
Group	0.30	0.5919
Time	0.61	0.5466
Group*Time	1.50	0.2335

Knee excursion

Effect	F	P-value
Group	4.86	.0373*
Time	1.28	.2881
Group*Time	2.65	.0809

* = $p < 0.05$

Peak vertical ground reaction force

Effect	F	P-value
Group	0.10	.7491
Time	0.42	.6589
Group*Time	3.51	.0378*

* p-value < 0.05

Peak vertical ground reaction force

Paired Contrasts	T	P value
Control Baseline vs. Experimental Baseline	-0.48	.6323
Control Baseline vs. Control Retention 1	-1.24	.2210
Control Baseline vs. Control Retention 2	-0.41	.6867
Control Retention 1 vs. Con Retention 2	0.83	.4084
Experimental Baseline vs. Experimental Retention 1	2.50	.0158*
Experimental Baseline vs. Experimental Retention 2	1.30	.2011
Experimental Retention 1 vs. Experimental Retention 2	-1.21	.2337

*p < 0.05

Appendix Q. ANOVA Tables: Stop-jump Task, Phase Two.

Approach speed

Effect	F	P-value
Group	1.47	.2371
Time	1.87	.1836
Group*Time	1.02	.3219

Peak internal knee adduction moment

Effect	F	P-value
Group	0.61	.4438
Time	0.51	.4816
Group*Time	0.22	.6411

Peak knee abduction angle

Effect	F	P-value
Group	0.06	.8046
Time	1.72	.2017
Group*Time	0.31	.5851

Peak internal knee extension moment

Effect	F	P-value
Group	0.25	.6250
Time	1.82	.1899
Group*Time	2.32	.1412

Knee excursion

Effect	F	P-value
Group	1.56	.2236
Time	0.70	.4126
Group*Time	0.01	.9388

Peak vertical ground reaction force

Effect	F	P-value
Group	1.01	.3252
Time	0.52	.4796
Group*Time	0.42	.5227

Appendix R. Group * Time Tables: Countermovement Jump, Phase One.

Peak knee adduction moment (Nm/kg)

		Time			
		Baseline	Retention 1	Retention 2	
Group	Experimental	0.55 (0.22)	0.44 (0.21)	0.54 (0.19)	0.51 (0.21)
	Control	0.44 (0.24)	0.49 (0.23)	0.49 (0.24)	0.47 (0.23)
		0.49 (0.23)	0.47 (0.22)	0.52 (0.21)	

Peak knee abduction angle (°)

		Time			
		Baseline	Retention 1	Retention 2	
Group	Experimental	-10.1 (4.1)	-10.3 (4.8)	-11.0 (3.8)	-10.5 (4.2)
	Control	-7.9 (2.7)	-9.3 (4.8)	-9.6 (4.3)	-8.9 (4.0)
		-9.0 (3.6)	-9.8 (4.7)	-10.3 (4.0)*	

Peak internal knee extension moment

		Time			
		Baseline	Retention 1	Retention 2	
Group	Experimental	2.28 (0.61)	2.06 (0.47)	2.11 (0.57)	2.15 (0.56)
	Control	2.24 (0.48)	2.16 (0.37)	2.21 (0.36)	2.20 (0.40)
		2.26 (0.54)	2.11 (0.42)	2.16 (0.47)	

Knee excursion (°)

		Time			
		Baseline	Retention 1	Retention 2	
Group	Experimental	66.2 (13.6)	75.4 (15.6)*	75.9 (17.4)*	72.5 (15.9)
	Control	59.1 (12.3)	60.4 (12.8)	59.4 (10.9)	59.6 (11.7)
		62.6 (13.2)	67.9 (16.0)	67.6 (16.5)	

Peak vertical ground reaction force (%BW)

		Time			
		Baseline	Retention 1	Retention 2	
Group	Experimental	1.81 (0.41)	1.60 (0.39)	1.62 (0.43)	1.68 (0.41)
	Control	1.73 (0.41)	1.68 (0.34)	1.72 (0.31)	1.71 (0.35)
		1.79 (0.40)	1.64 (0.36)	1.67 (0.37)*	

Appendix S. Group * Time Tables: Stop-jump Task, Phase One.

Peak internal knee adduction moment (Nm/kg)

		Time		
		Baseline	Transfer	
Group	Experimental	0.83 (0.42)	0.77 (0.41)	0.80 (0.41)
	Control	0.70 (0.26)	0.72 (0.25)	0.71 (0.25)
		0.77 (0.35)	0.74 (0.33)	

Peak knee abduction angle (°)

		Time		
		Baseline	Transfer	
Group	Experimental	-13.2 (5.4)	-13.5 (5.7)	-13.4 (5.4)
	Control	-13.4 (6.4)	-15.1 (6.0)	-14.2 (6.2)
		-13.3 (5.8)	-14.3 (5.8)	

Peak internal knee extension moment (Nm/kg)

		Time		
		Baseline	Transfer	
Group	Experimental	2.63 (0.52)	2.50 (0.47)	2.56 (0.49)
	Control	2.67 (0.66)	2.57 (0.60)	2.62 (0.62)
		2.65 (0.58)	2.53 (0.53)	

Knee excursion (°)

		Time		
		Baseline	Transfer	
Group	Experimental	45.9 (9.9)	47.7 (11.9)	46.8 (10.8)
	Control	50.6 (10.1)	49.5 (11.6)	50.0 (10.7)
		48.3 (10.1)	48.6 (11.6)	

Peak vertical ground reaction force (%BW)

		Time		
		Baseline	Transfer	
Group	Experimental	2.15 (0.72)	2.12 (0.75)	2.14 (0.72)
	Control	1.86 (0.52)	1.88 (0.58)	1.87 (0.54)
		2.00 (0.63)	2.00 (0.67)	

Appendix T. Group * Time Tables: Countermovement Jump, Phase Two.

Peak internal knee adduction moment (Nm/kg)

		Time			
		Baseline	Retention 1	Retention 2	
Group	Experimental	0.55 (0.22)	0.48 (0.18)	0.53 (0.18)	0.52 (-0.19)
	Control	0.44 (0.24)	0.49 (0.25)	0.56 (0.21)	0.50 (0.23)
		0.49 (0.23)	0.49 (0.21)	0.55 (0.19)	

Peak knee abduction angle (°)

		Time			
		Baseline	Retention 1	Retention 2	
Group	Experimental	-10.1 (4.1)	-9.9 (2.7)	-10.3 (4.1)	-10.2 (3.5)
	Control	-7.9 (2.7)	-8.1 (4.0)	-10.1 (4.4)	-8.7 (3.8)
		-9.0 (3.6)	-9.2 (3.4)	-10.2 (4.1)	

Peak internal knee extension moment (Nm/kg)

		Time			
		Baseline	Retention 1	Retention 2	
Group	Experimental	2.28 (0.61)	2.08 (0.40)	2.15 (0.38)	2.17 (0.47)
	Control	2.24 (0.48)	2.29 (0.49)	2.25 (0.38)	2.26 (0.44)
		2.26 (0.54)	2.18 (0.45)	2.20 (0.38)	

Knee excursion (°)

		Time			
		Baseline	Retention 1	Retention 2	
Group	Experimental	66.2 (13.6)	69.7 (16.3)	71.7 (18.5)	69.2 (16.0)
	Control	59.1 (12.3)	56.0 (10.9)	58.3 (10.4)	57.8 (11.0)
		62.6 (13.2)	62.9 (15.3)	65.0 (16.2)	

Peak vertical ground reaction force (%BW)

		Time			
		Baseline	Retention 1	Retention 2	
Group	Experimental	1.81 (0.41)	1.64 (0.40)	1.72 (0.38)	1.72 (0.39)
	Control	1.73 (0.41)	1.81 (0.42)	1.76 (0.39)	1.77 (0.40)
		1.77 (0.40)	1.73 (0.41)	1.74 (0.38)	

Appendix U. Group * Time Tables: Stop-jump Task, Phase Two.

Peak internal knee adduction moment (Nm/kg)

		Time		
		Baseline	Transfer	
Group	Experimental	0.83 (0.42)	0.85 (0.40)	0.84 (0.40)
	Control	0.70 (0.26)	0.77 (0.35)	0.74 (0.30)
		0.77 (0.35)	0.81 (0.37)	

Peak knee abduction angle (°)

		Time		
		Baseline	Transfer	
Group	Experimental	-13.2 (5.4)	-13.8 (6.4)	-13.5 (5.5)
	Control	-13.4 (6.4)	-14.9 (7.0)	-14.1 (6.6)
		-13.3 (5.8)	-14.3 (6.6)	

Peak internal knee extension moment (Nm/kg)

		Time		
		Baseline	Transfer	
Group	Experimental	2.63 (0.52)	2.63 (0.45)	2.63 (0.48)
	Control	2.67 (0.66)	2.81 (0.65)	2.74 (0.64)
		2.65 (0.58)	2.72 (0.55)	

Knee excursion (°)

		Time		
		Baseline	Transfer	
Group	Experimental	45.9 (9.9)	44.9 (9.8)	45.4 (9.6)
	Control	50.6 (10.2)	49.8 (10.6)	50.2 (10.2)
		48.3 (10.1)	47.3 (10.3)	

Peak vertical ground reaction force (%BW)

		Time		
		Baseline	Transfer	
Group	Experimental	2.15 (0.72)	2.15 (0.74)	2.15 (0.71)
	Control	1.86 (0.52)	1.95 (0.61)	1.90 (0.56)
		2.00 (0.63)	2.05 (0.67)	

Vita

Jeremiah Tate received his bachelor's of physical therapy degree from the University of Tennessee at Chattanooga in 1999. After working for three years as a physical therapist, he returned to school at the University of North Carolina at Chapel Hill. In 2005, he received his master's degree in Human Movement Science and received the Mary Clyde Singleton Award. Following graduation, Jeremiah accepted an adjunct faculty position within the department of physical therapy at The University of Tennessee at Chattanooga where he taught biomechanics and orthopaedics. He enrolled in the PhD program at the University of Tennessee at Knoxville in the Fall of 2006. His research focused on real-time biofeedback for gait retraining and technique training related to biomechanical risk factors associated with ACL injury risk. Upon graduation, he accepted a faculty position within the physical therapy department at Lynchburg College (Lynchburg, VA).