This is to certify that the
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INFLUENCE OF A DEXTERITY TRAINING PROTOCOL ON
BIOMECHANICAL PARAMETERS OF THE KNEE JOINT AMONG
ADOLESCENT FEMALE BASKETBALL PLAYERS

presented by

Anthony Moreno

has been accepted towards fulfillment
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INFLUENCE OF A DEXTERITY TRAINING PROTOCOL ON BIOMECHANICAL PARAMETERS OF THE KNEE JOINT AMONG ADOLESCENT FEMALE BASKETBALL PLAYERS

By

Anthony Moreno

A DISSERTATION

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ABSTRACT

THE INFLUENCE OF A DEXTERITY TRAINING PROTOCOL ON BIOMECHANICAL PARAMETERS OF THE KNEE JOINT AMONG ADOLESCENT FEMALE BASKETBALL PLAYERS

By

Anthony Moreno

The purpose of this study was to examine the effects of a dexterity protocol on biomechanical parameters of the knee joint among competitive adolescent female basketball athletes landing on a force platform from a maximal vertical jump effort, and subsequently performing an unanticipated directional sprint task. Peak ground reaction forces (PGRF), peak knee joint flexion (PKJF), time to peak knee joint flexion (TKJF), and peak knee extension moments (PKJM) were collected among six adolescent female basketball players from two randomly solicited elite-for-age teams placed into two groups, experimental (n=4; mean = 13.75 yr.) and control (n=2; mean age = 13.85yr.). In addition to their regular practice and competition schedule, the experimental group was exposed to a six week dexterity training intervention, while controls followed their typical practice and competition routine.

Pre-intervention dependent variables were analyzed with an independent sample t-test and revealed TKJF exhibited the lone significant pre-existing group difference with the unanticipated landing condition. Post intervention biomechanical parameters for both anticipated and unanticipated landing conditions were calculated and evaluated through the use of descriptive statistics. To test the hypotheses related to potential group differences over time, a series of repeated-measures analysis of variance (ANOVAs), utilizing a mixed model analysis, was performed for each of the dependent variables. For

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the unanticipated vertical jump landing condition, results of the ANOVAs revealed no significant main effect of the dexterity protocol for mean PGRF, PKJF, TKJF, and PKJM.

Pearson's correlations were performed to determine if relationships among the dependent variables existed, with both unanticipated and anticipated conditions. Unanticipated PKJF and unanticipated TKJF exhibited a moderately strong relationship ($r = .72$, $p < .01$), while anticipated TKJF exhibited a moderate association with anticipated PKJF ($r = .58$, $p < .01$) and a moderate inverse relationship with anticipated PKJM ($r = -.58$, $p < .01$). To determine if significant pre-intervention differences existed between the anticipated and unanticipated landing condition among all participants, a paired sample t-test was conducted for each dependent variable. Mean values for PGRF, PKJF, TKJF, and PKJM were significantly different when comparing the anticipated to the unanticipated landing condition implying the use of different landing strategies with unpredictable situations.

Despite the lack of significance among the dependent variables with the unanticipated landing condition, mean values for PKJF and TKJF did exhibit hypothesized trends in that the six week dexterity protocol would respectively generate increases in peak knee joint angular excursion and time to peak knee joint flexion, upon impact with the force platform. Future investigations should further explore potential disparities among anticipated and unanticipated landing scenarios to examine if anterior cruciate ligament (ACL) injury intervention protocols must provide greater variability and unpredictability, thus, lending greater insight in the attempt to manage those extrinsic factors associated with non-contact ACL injury among adolescent female athletes.

DEDICATION

This dissertation is dedicated to my parents, Frances L. and Ricardo G. Moreno.

ACKNOWLEDGEMENTS

Foremost, I would like to thank David Mullineaux Ph.D. for his input, guidance, and technical assistance throughout all stages of this dissertation. This research project could not have been accomplished without his selfless permission, support, and time. I would also like to thank and recognize the significant contributions of my dissertation committee, John Haubensticker Ph.D., Tracey Covassin Ph.D., and Mark Reckase Ph.D.

I would like to express my sincere gratitude to Eugene Brown Ph.D., my major advisor, for his acceptance, patience, confidence, and guidance throughout my doctoral studies and for providing me the opportunity to become a new investigator and better teacher. Special thanks to Miguel Narvaez, Kris Kotrola, Lynette Craft Ph.D., and Adam Bruenger for their time and assistance throughout all stages of data collection and the preparation of this document. I would also like to recognize Gail Dummer Ph.D., Robert "Bob" Malina Ph.D., and Vern Seefeldt Ph.D. for sharing their time, insight, and research experiences with both able-bodied and disabled youth during my tenure as a doctoral student.

Finally, thank you to my sons, Colton and Cade, who give me the energy and inspiration to try to be the best I can be every single day, and last but definitely not the least, my wonderful wife Tracy, for her tolerance and continuous support of all my personal endeavors throughout the years. Thank you.

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CHAPTER 1

INTRODUCTION

Overview of the Problem

Anterior cruciate ligament (ACL) injuries are among the most devastating and frequent injuries encountered in recreation, sport, and workplace. Current epidemiological data reports the incidence of ACL injury to occur to one in every 3000 persons, with approximately 70% of these related to sports participation (Chappell, Yu, Kirkendall, & Garrett, 2002; Colby, Francisco, Yu, Kirkendall, Finch, & Garrett, 2000; Huston, Greenfield, & Wojtys, 2000). Of great concern is the fact that the incidence of non-contact ACL injuries is two to eight times greater among female participants when compared to their male counterparts competing in similar sports (Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001; Harmon & Ireland, 2000; Kirkendall & Garrett, 2000; Hewett, 2000; Heidt, Sweeterman, Carionas, Traub, & Tekulve, 2000; Hosea, Carey, & Harrer, 2000; McLean, Neal, & Myers, 1999; Demont, Lephart, Giraldo, Swanik, & Fu, 1999; Heitz, Eisenman, Beck, & Walker, 1999; Huston & Wojtys, 1996; Ireland, 1999; Arendt & Dick, 1995).

Significance of the Problem

Injuries sustained with high frequency and severity may develop into medical scenarios that generate into important health concerns. The National Collegiate Athletic Association (NCAA) has documented an average knee injury rate of ten% among female participants, and given there are approximately 130,000 female intercollegiate athletes participating each year in the NCAA, it can be estimated that approximately 13,000 ACL inju

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injuries of varying severity may occur to these female participants at the intercollegiate level (NCAA, 1997).

In 1997, the National Federation of State High School Associations reported more than 2.5 million girls participate in high school sports programs during the course of a given year. Although the rate of knee injury for most female participant sports is not known for high school populations, if they approximate those at the intercollegiate level on the basis of NCAA incidence figures, it is estimated that 25,000 ACL injuries could occur among the 2.5 million participants over one year (Huston et al., 2000).

Hewett et al. (1999) has reported that, for female participants of high school basketball, ACL injuries occur at an annual rate of approximately one in 65 participants. In 2002, the National Federation of State High School Associations reported 452, 728 female basketball players participated at the high school level in the United States. Given the incidence figures reported by Hewett et al. (1999), it is estimated that approximately 7,000 ACL injuries may occur to female high school basketball athletes on an annual basis.

Powell and Barber-Foss (2000), in a cohort observational study utilizing certified athletic trainers, found the rate of female high school athletes to undergo ACL surgical procedure four times as often as their male counterparts and were 44% more likely to injure the ACL than their male counterparts. They also found injury rates, knee surgery rates, and, specifically ACL surgery rates for girls' high school basketball players, similar to those rates found for women participating at the levels of intercollegiate and Olympic basketball. In concert with epidemiological studies conducted at the intercollegiate level, the investigators of this study found high school basketball to not be a unique sport in the incid

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incidence and severity of ACL injuries when comparing the frequency to their male counterparts. When identifying patterns by sport, soccer possesses similarities to basketball in that females exhibit significantly higher ACL injury rates when compared to their male counterparts (Powell & Barber-Foss, 2000).

These findings support the hypothesis that there is greater risk of knee injury and knee surgery for female athletes at the competitive intercollegiate and high school levels. This manifest difference in injury rate of the ACL between females and males has spurred efforts by researchers to determine why there is such disparity between genders. This issue is given greater significance since the passage of Title IX in 1972 as a federal mandate that has dramatically expanded the number of opportunities for females in sport from the recreational youth level to professional sport. In conjunction with these higher participation rates comes the realization that these same opportunities enhance the potential for increasing the quantity of serious knee injuries (Hosea et al., 2000; Hewitt, 2000; Powell & Barber- Foss, 2000; Delfico & Garrett, 1998).

Hutson et al. (2000) reported the average monetary cost per ACL surgery and rehabilitation to be approximately $17,000 in the United States. Based upon injury estimates from Hewett et al. (1999), it is estimated that ACL injuries among female athletes at the high school level have the potential to cost approximately $119 million dollars on an annual basis. These figures do not reflect the costs associated with other lower extremity anomalies (e.g., stress fractures of the foot, ankle injuries) and it must be considered that these incidents contribute to other costly and rehabilitative conditions such as emotional distress, depression, poor academic performance, unstable mental health, and post traumatic arthritis (Shea, Apel, & Pfeiffer, 2003; Hewett, 2000).

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Statement of the Problem

The purpose of this study was to examine the effects of a dexterity training intervention on peak ground reaction forces (PGRF), peak knee joint flexion (PKJF), time to peak knee joint flexion (TKJF), and peak knee extension moments (PKJM) of competitive adolescent female basketball athletes landing on a force platform from a maximal vertical jump effort and immediately performing an unanticipated directional sprint task.

Need for the Study

A review of the pertinent epidemiological literature with respect to ACL injury has revealed that there are several potential injury mechanisms that may play a vital role in defining the significant gender disparity observed in sports-related non-contact ACL injury rates (Hewett, Myer, & Ford, 2006; McClean, et al., 1999). These proposed injury mechanisms are typically categorized as intrinsic or extrinsic factors (Hewett et al., 2006; Huston et al., 2000).

Intrinsic factors are those features that include intra-individual characteristics such as growth and maturation, lower extremity skeletal misalignment, insufficient muscular strength, poor joint mobility, excessive joint laxity, and hormonal mechanisms. Intrinsic factors are typically difficult to control and may not be modifiable (Harmon & Ireland, 2000). Unlike intrinsic factors, extrinsic factors may be modifiable and include such mechanisms as neuromuscular proficiency, individual motor competence, musculo-skeletal agonist-antagonist joint strength ratios, supervision and instruction, playing surface, level of competition, and equipment (Hutson et al., 2000). Although it is generally understood that these intrinsic and extrinsic mechanisms are interdependent, the e

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interactions between learning and coaching environment, physical structure and endocrine systems can be extremely influential on neuromuscular function, bone growth, and ligamentous integrity (Fulkerson & Arendt, 2000).

Although the quantity of biomechanical studies regarding ACL injury has increased, those specifically involving female adolescent athletic populations are sparse. Despite the fact that great strides have been accomplished in achieving greater understanding into the ACL injury gender-bias (Hewett, 2000; Harmon & Ireland, 2000; Huston & Wojtys, 1996; Ireland, 1999; Arendt & Dick, 1995), the vast majority of these research efforts have utilized intercollegiate or adult populations to support the findings. The available data on adolescent female athletes is lacking and remains a population from which greater information should be collected and analyzed with respect to their differing and dynamically maturing anatomical and physiological systems, when compared to their physically advanced intercollegiate peers.

Because intrinsic factors (e.g., anatomical and/or hormonal characteristics) cannot be viably addressed in the field setting, research emphases have shifted toward understanding the influence of agility, perturbation, and plyometric training protocols that provide the opportunity to alter lower extremity neuromuscular strategies and potentially play a role in modifying the extrinsic factors (e.g., muscle activity and/or gross motor competence). This study will address the influence of a dexterity protocol on biomechanical parameters of the knee joint. In addition, it is the intent of this research paradigm to determine if there are potential "windows" of opportunity at particular developmental ages where neuro-mechanical pliability can be enhanced. In particular, at ages where dynamic morphological and physiological changes are concurrent with the p

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acquisition of fundamental and special motor skills that may play a vital role in modifying those special biomechanical parameters associated with ACL injury.

The utility of introducing physical training protocols at a developmental age may provide a reliable intervention method through which the alarming ACL injury gender-bias can be potentially attenuated. Further, the opportunity to administer those interventions in sufficient doses at dynamic stages of growth and development may mitigate the incidence of non-contact ACL injuries among those female athletes that intend to participate in competitive or recreational play throughout high school, college, and adulthood.

Hypotheses

The previously presented research paradigm suggests the following four research hypotheses:

Hypothesis 1. In comparison to controls, participants of the experimental group will exhibit lower ground reaction forces at landing under unanticipated conditions after following the twice per week, six week dexterity training protocol.

Hypothesis 2. In comparison to controls, participants of the experimental group will exhibit greater angular ranges of knee joint flexion on landing under unanticipated conditions after following the twice per week, six week dexterity training protocol.

Hypothesis 3. In comparison to controls, participants of the experimental group will exhibit greater time to maximum knee joint flexion on landing under unanticipated conditions following the twice per week, six week dexterity training protocol.

Hypothesis 4. In comparison to controls, participants of the experimental group will exhibit decreased peak extensor moments of the knee joint on landing under unanticipated conditions following the twice per week, six week dexterity training protocol.

Limitations

- The participants of this study compete in an Amateur Athletic Union (AAU) basketball league and are considered to possess superior basketball skills when compared to their age-group peers. Thus, the participants of this study may not be representative of all adolescent female basketball players that compete at other levels.
- For this study, the influence of a dexterity training program on the hypothesized dependent variables was conducted with a relatively small sample size. Limitations with respect to sample size make it arduous to interpret the results of the data analysis.

Assumptions

The following assumptions with respect to the participants and the research design were made to draw conclusions from the results.

- The participants of the study were representative of other elite female adolescent basketball players who participate in an AAU competitive basketball league.
- Because elite-level female adolescent basketball players demonstrate superior basketball skills, it was expected that their specialized training enabled them to demonstrate enhanced motor ability when compared to their age-group peers at lower levels of competitive basketball.

- The participants did not engage in any recreational or competitive physical activity outside of practice and the preparative environment typical of an elite female adolescent basketball athlete.

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Definitions

Acceleration. The rate of change of velocity.

Agility. The process by which the degrees of freedom of a body segment or segments are organized in space and time and sequence to produce a functional motor response to an atypical motor environment.

Analog-to-digital conversion (A/D). The process of taking a continuous signal and sampling it over time to create an array of discrete digital values that represent the original signal.

Angular acceleration. The rate of change of angular velocity.

Angular displacement. The change in angular position.

Angular velocity. The rate of change of angular displacement.

Anterior tibial drawer effect. Anterior directed translation of the tibia with respect to the position of the femur upon impact from a jump landing or a cutting-type maneuver.

Anthropometrics. The measurement of physical properties associated with the human body.

Anticipated directional sprint task. Prior to performing a maximal vertical jump effort, the participant is made aware of the direction (left or right) with which to sprint two meters upon immediate contact with the laboratory floor surface.

Biomechanics. The study which applies the principles of mechanics to living things.

Center of mass/gravity. The point that represents the total weight/mass distribution of a body. The mass centriod is the point where the mass of the object is balanced in all directions.

Chondromalacia. Uncharacteristic softening of skeletal cartilage.

Concentric muscle action. The condition where activated muscle(s) create a torque greater than a resistance torque resulting in a movement of a segment of the body in the direction of the action of the muscles.

Coordination. The process by which the degrees of freedom are organized in space and time and subsequently produce a functional movement pattern.

Countermovement jump. Rapid flexion at the hip and knee, concurrent with dorsiflexion at the ankle, that elicits eccentric loading of the lower extremity musculature immediately prior to the concentric phase of a jump.

Cut-off frequency. The cutting point of a filtering technique applied to an array of data, where frequencies above or below a designated frequency are removed. The lower the cut-off frequency for a low-pass filter the greater the smoothing of the signal.

Degrees of freedom. The number of independent movements an object or body part (e.g., limb segment) may create, and consequently the number of measurements necessary to document the kinematics of the object or body part.

Dexterity. The process by which the degrees of freedom of a body segment or segments are organized in space and time and sequenced to produce if necessary, a rapid motor solution to an unpredictable motor problem with varying spatial, temporal, and sequential elements.

Dexterity protocol. Physical training program that includes selected motor exercises with varying spatial, temporal, and sequential elements.

Digitize. The process of measuring two-dimensional locations of points on an image.

Displacement. Change in position of some point in a particular direction.

Dynamics. The branch of mechanics studying the motion of bodies under acceleration.

Dynamic restraint components. Proprioceptive components (e.g., muscle spindles, golgi tendon organs) that regulate the activity of skeletal muscles that literally cross an articulation to help provide functional joint stability via concentric, eccentric, and/or isometric muscle contractions.

Eccentric muscle action. The condition where activated muscle(s) create a torque less than a resistance torque resulting in a movement of a segment of the body in the opposite direction of the action of the muscle(s).

Electromyography (EMG). The recording, processing, and amplification of the electrical signal of active muscle.

Energy (mechanical). The ability to do mechanical work.

Engram. Neural activity used in the assembly and execution of a motor pattern.

External work. Work done on a body by an external force.

Extrinsic injury factors. Extrinsic injury factors are typically modifiable and include such areas as neuromuscular proficiency, motor competence, musculoskeletal agonist-antagonist joint-strength ratios, supervision and instruction, playing surface, level of competition, and equipment.

Femoral anteversion. An anatomical condition where the femoral head and neck are rotated anterior to an imaginary line directed through the femoral condyles in the horizontal plane.

Foot pronation. Combined eversion and abduction motions of the foot.

Force. An influence that either pushes or pulls and can act to alter the motion or shape of an object.

Force platform. A complex force transducer that measures all three orthogonal forces and moments applied to its surface.

Frame (video). One complete video image.

Genu Valgum. Anatomical condition associated with a "knock-kneed" disposition.

Genu Varus. Anatomical condition associated with a "bowlegged" disposition.

Global reference frame. Measuring kinematics relative to an unmoving coordinate system on the earth.

Ground reaction force. Common three-dimensional force vector acting on the body that occurs with typical standing, running, or jumping activities.

Intercondylar notch width. The distance between the two distal femoral condyles at the level of the popliteal groove.

Intercondylar impingement. During extension of the knee, the anterior cruciate ligament may impinge upon the area designated as the anterior intercondylar notch.

Internal work. Work done on defined systems of the body by internal forces within these systems.

Intrinsic injury factors. Factors that include intra-individual characteristics such as growth, maturation, lower-extremity alignment, muscular strength, joint mobility, joint laxity, and the endocrine system.

Inverse dynamics. Biomechanical research technique used to estimate net forces and moments in a linked segment model from measured kinematics, kinetics, and anthropometric data.

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Isokinetic muscle action. That condition where the angular velocity of a segment's movement is constant regardless of the concentric torque produced by a muscle or muscle group.

Isometric muscle action. The condition where activated muscle(s) create(s) a torque equal to the resistance torque and the angular velocity of the associated segment equals zero.

Isotonic muscle action. Dynamic condition with a constant resistance and a varying muscle tension because of factors associated with the changing muscle moment.

Joint center. An approximation of the instantaneous center of rotation of a joint.

Kinematics. A subdivision of dynamics that is concerned with a quantitative description of an object's position in space, velocity, and acceleration without regard for the forces involved.

Kinesthesia. Knowledge of one's position and orientation of a body segment in space or its relative position in reference to another body segment.

Kinetics. A subdivision of dynamics that is concerned with the effects of forces on some object, segment, or body.

Lateral rotation of the knee. An outwardly-directed rotation at the knee joint with respect to the anatomical reference position of the human body.

Load. A force or moment applied to an object.

Local reference frame. Measuring kinematics relative to a moving coordinate system on a nearby rigid body (joint, segment, or center of mass).

Low pass filter. A signal processing technique that removes high frequency components from an array of data.

Medial rotation. An inwardly-directed rotation at the knee joint with respect to the anatomical reference position of the human body.

Moment (moment of force, torque). The rotational effect of a force applied to a lever.

Moment arm. The leverage of a force for creating a moment. The perpendicular distance from the axis of rotation to the line of action of the force.

Moment of inertia. The resistance to rotation of a body.

Motor (efferent) pathway. Neural pathway with which impulses from the brain and spinal cord innervate musculature and glands.

Motor unit. A motor neuron and all the muscle fibers it innervates.

Muscle stiffness. Regulated by proprioceptive feed forward and feedback mechanisms, it is the ratio of the change in applied force per change in length of the muscle.

Neuromuscular control. The elaborate nervous and muscular mechanisms that comprise the nervous system and delineate their role in voluntary, involuntary, and reflexive muscle activation.

Newton (N). The metric unit of force. One Newton is equal to 0.22 pounds.

Notch width index (NWI). Ratio determined by comparing the width of the femoral intercondylar notch to the distance between the two distal femoral condyles at the level of the popliteal groove.

Passive restraint components. The ligamentous and cartiligenous structures, joint capsules, and bony arrangements about an articulation that help provide functional joint stability.

Patello-femoral distress syndrome. Lateral deviation of the patella as it tracks in the femoral groove.

Patello-femoral tracking. The appropriate anatomical and central disposition of the patella with respect to the femoral groove of the knee joint complex.

Perturbation training. Physical training that involves the maintenance of lower extremity balance during the disturbance of the support surfaces.

Patello-femoral tracking. Tracking of the patella within the femoral groove of the femur.

Peak ground reaction force (PGRF). The highest instantaneous ground reaction force as participant's of the study made contact with the force platform following a maximal vertical jump effort.

Peak knee extension moment (PKJM). The highest instantaneous rotational force (torque) produced by the knee extensor musculature to oppose knee joint flexion during landing and indicative of the muscles role as a shock absorber.

Peak knee joint flexion (PKJF). The maximum amount of knee joint displacement with reference to the angle formed by the right thigh and lower leg segments as participant's of the study made contact with the force platform following a maximal vertical jump effort.

Plyometric training. Method of physical training technique used to enhance muscular power utilizing a rapid stretch-shortening contraction of a muscle or muscle group to entice greater rate of force development.

"Position of no return". Jump landing condition that exhibits simultaneous femoral anteversion, external tibial rotation, and foot pronation.

Power (mechanical). The rate of doing mechanical work that represents the product of force and velocity. Power can be calculated as Work/Time or Force x Velocity.

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Proprioception. The culmination of all sensory inputs originating from the visual apparatus, vestibular system, and peripheral mechanoreceptors of various musculoskeletal structures.

Q-angle. The Q- or quadriceps angle is defined as the acute angle between the line connecting the anterior suprailiac spine (ASIS) and the midpoint of the patella, and the line connecting the tibial tuberosity with that same patellar reference point.

Quickness. The process by which the degrees of freedom of a body segment or segments are organized in space and time and sequence to produce a rapid functional motor response to an atypical motor environment.

Recruitment. The activation of motor units within muscles by the central nervous system.

Reflective markers. High-contrast reflective materials attached to subjects to facilitate the location of segments or joint centers for digitizing the locations of these segments or joints in frames of video.

Rigid body. Mechanical simplification (abstraction) assuming the dimensions of an object do not change during movement and loading.

Sampling rate. The number of discrete samples per second used to represent a continuous signal.

Sensorimotor system. Neurological apparatus responsible for the regulation of the interaction between the sensory (afferent) and motor (efferent) pathways.

Sensory (afferent) pathway. Neural pathway with which impulses from peripheral sense organs, skin, and viscera are directed to the brain and spinal cord.

Shear. Mechanical loading in opposite directions and at right angles to the surface of a material.

Skeletal dimorphism. Differences among skeletal bone structures typically defined by sex (male or female) and/or behavior.

Statics. The branch of mechanics studying bodies at rest or uniform motion.

Strain. The amount of deformation of a material by an applied force, usually expressed as a percentage change in the original dimensions of the material.

Strength (muscular). The maximum force or torque produced by a muscle or muscle group at a specific joint angle. Research has found several domains of strength expression depending on the time, velocity, and resistance involved.

Stress (mechanical). The force per unit area expressed upon an object.

Stretch-shortening cycle (SSC). Muscle agonists for a movement are eccentrically loaded during a countermovement, and immediately before the concentric action. SSC enables greater initial force and concentric work than concentric actions alone.

Tension. Mechanical loading created by forces in opposite and non-centric directions acting along a longitudinal axis.

Time to peak knee joint flexion (TKJF). The recorded time (sec.) for each participant, commencing with initial contact with the force platform until peak knee joint flexion, upon performing a maximal vertical jump effort.

Unanticipated directional sprint task. Prior to performing a maximal vertical jump effort, the participant is not aware of the direction (left or right) with which they are to sprint two meters upon immediate contact with the laboratory floor surface.

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Valgus stress. Inward or knock-kneed predisposition that places mechanical stress on medial structures of the knee joint.

Varus stress. Outward or bow-legged predisposition that places mechanical stress on lateral structures of the knee joint.

Vector. A complex quantity expressing magnitude and direction (e.g., force, velocity).

Weight. Vertical resistance of a mass due to gravitational force.

Work (mechanical). Positive work is done when a force moves an object in the direction of the force and is calculated by the product of force and displacement.

CHAPTER 2

REVIEW OF LITERATURE

Current epidemiological data reports the incidence of ACL injury to occur to one in every 3,000 persons, with approximately 70% of these related to sports participation (Chappell et al., 2002; Colby et al., 2000; Huston et al., 2000). For female participants of recreational and competitive sport, these figures become even more alarming when the prevalence of non-contact ACL injury is two to eight times greater when compared to their male counterparts competing in similar sports (Malinzak et al., 2001; Harmon & Ireland, 2000; Kirkendall & Garrett, 2000; Hewett, 2000; Heidt et al., 2000; Hosea et al., 2000; McLean et al., 1999; Demont et al., 1999; Heitz et al., 1999; Huston & Wojtys, 1996; Ireland, 1999; Arendt & Dick, 1995).

The passage of Title IX of Education Amendments in 1972 as a federal mandate has dramatically increased the number of opportunities for girls and women in sport. Today, women comprise 35% of the total intercollegiate participants compared to only 15% in 1972. In conjunction with these higher participation rates comes the realization that these same opportunities enhance the potential for increasing the quantity of serious knee injuries (Hosea et al., 2000). Injuries sustained with high frequency and severity can generate medical scenarios that develop into important health concerns. The NCAA documented an average knee injury rate of 10% for female athletes within one year. Given there are approximately 130,000 female intercollegiate athletes, approximately 13,000 ACL injuries of varying severity may occur to females that participate at the intercollegiate level (NCAA, 1997).

In 1997, the National Federation of State High School Associations reported more than 2.5 million girls participate in high school sports programs during the course of a given year. Although the rate of knee injury for most female-participant sports is not known for high school populations, if they approximate those at the intercollegiate level on the basis of NCAA incidence figures, it could be estimated that 25,000 ACL injuries may occur among the 2.5 million participants (Huston et al., 2000).

Hewett et al. (1999) has reported that, for female participants of high school basketball, ACL injuries occur at an annual rate of approximately one in 65 participants. In 2002, the National Federation of State High School Associations reported 452, 728 female basketball players participated at the high school level in the United States. Given the incidence figures reported by Hewett et al. (1999), it is estimated that approximately 7,000 ACL injuries may occur to female high school basketball athletes on an annual basis.

Huston (2000) reported the average monetary cost of ACL surgery and rehabilitation to be approximately $17,000 in the United States. Based upon injury estimates from Hewett et al. (1999), it is estimated that ACL injuries among female athletes at the high school level have the potential to cost approximately $119 million dollars on an annual basis. These figures do not reflect the costs associated with other lower extremity orthopedic anomalies (e.g., stress fractures of the foot, ankle injuries), and it must be considered that these incidents contribute to other costly rehabilitative conditions such as emotional distress, depression, poor academic performance, unstable mental health, and post traumatic arthritis (Shea et al., 2003; Hewett, 2000).

Because of the steady increase in the number of females participating in sport, there exists a potential for these conditions to become further exacerbated. To help decrease this potential, it becomes necessary to fully understand those environmental, anatomical, physiological, and neuromuscular mechanisms that are suggested to contribute to the ACL dilemma. Once these important factors have been identified, the creation of abatement programs may become valuable tools that may help stem the increasing incidence of ACL injury.

Function of the ACL

Stability of the human knee joint is chiefly provided by the collateral ligaments on the medial (tibial collateral) and lateral (fibular collateral) sides of the joint, and the anterior and posterior cruciate ligaments (Figures 1 and 2) within the joint capsule. In addition to these ligaments that bind the bones of the joint together, there are various muscular, tendinous, and ligamentous expansions that also help to stabilize the joint. Muscle in particular plays a protective role in joint stabilization by 1) strain relief of the ligaments and 2) impact absorption of the loads transmitted through the lower extremity (Withrow, Huston, Wojtys, & Ashton-Miller, 2006; Wojtys & Huston, 2000). The complex arrangement of these tissues with respect to the skeletal structure of the knee joint is reviewed and described in detail by Aiello and Dean (1999).

The ACL arises from the anterior intercondylar space on the tibial plateau, runs upwards and posteriorly, and attaches on the inside of the lateral condyle of the femur. This ligament becomes taut as the knee joint extends and chiefly prevents the femur from sliding posteriorly off the tibial plateau (Wojtys & Huston, 2000; Aeillo & Dean, 1999; MacWilliams, Wilson, DesJardins, Romero, & Chao, 1999). The posterior cruciate ligament (PCL) arises from back on the intercondylar space of the tibial plateau, runs upward and anteriorly, and attaches on the inside of the medial femoral condyle. The PCL becomes taut as the knee joint is flexed and thus prevents the tibia from sliding anteriorly off the tibial plateau (Aeillo & Dean, 1999).

Another chief function of the cruciates is to limit medial rotation of the tibia in relation to the femur. With medial rotation of the tibia with respect to the femur, the cruciates twist around each other to aid in preventing further rotation. However, in lateral rotation, they untwist and have no limiting ability (Aeillo & Dean, 1999).

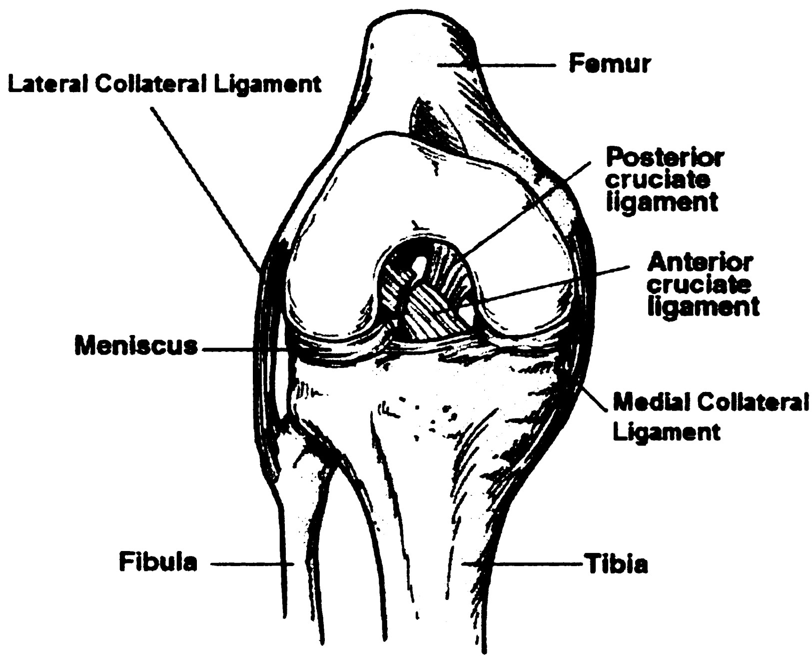

Figure 1. Anterior view of the right knee joint.

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[1]Retrieved August 31st, 2005 from the World Wide Web: http://www.steadman-hawkins.com/virtual/education/acl.html

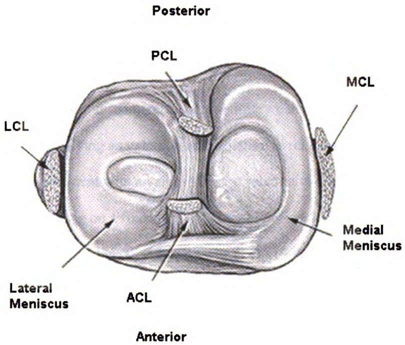

Figure 2. Superior view of the right knee joint.

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[2]Retrieved August 31st, 2005 from the World Wide Web: http://www.arthroscopy.com/sp05001.htm

Mechanism of Injury

Efforts to identify the special circumstances with which ACL injuries occur among female athletes indicate the majority of incidents are typically non-contact in nature, occurring while the athlete is landing from a jump or conducting a pivoting or sidestep cutting-type maneuver (McClean et al., 1999). Hewett (2000) has reported that approximately 80% of all ACL injuries occur via non-contact mechanism after landing from a jump. Investigations utilizing retrospective injury data have further described this injury mechanism as involving an external tibial rotation in relation to an internal femoral rotation (Figure 3), coincident with a valgus stress at relatively low knee flexion angles, while suddenly decelerating on a fixed or planted foot (Dorizas & Stanitski, 2003; Kirkendall & Garrett, 2000; Hewett, 2000; Rosene et al., 1999; Wilk et al., 1999; Delfico & Garrett, 1998; Cross, Gibbs, & Bryant, 1989).

Ireland (1999) has labeled one particular state of femoral anteversion, external tibial rotation, and concurrent foot pronation as the "position of no return" (Figure 4), while others have simply referred to this circumstance as "miserable-mal-alignment" (Fulkerson & Arendt, 2000). Chappell et al. (2002) have indicated that landing from a jump in concert with enhanced extension and valgus moments at the knee and deceleration of the body, is conducive to producing an anterior shear force at the proximal tibia that contributes to an anterior tibial translation with respect to the femur (Figure 5). It is believed that this anterior tibial "drawer" effect places the ACL ligament in a vulnerable position upon landing or cutting and exacerbates the conditions through which partial or complete mechanical failure of the ACL is accomplished.

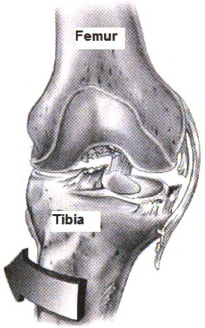

Figure 3. External tibial rotation at the right knee relative to the femur.

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[3]Retrieved August 31st, 2005 from the World Wide Web: http://www.hughston.com/hha/b_11_3_2b.jpg

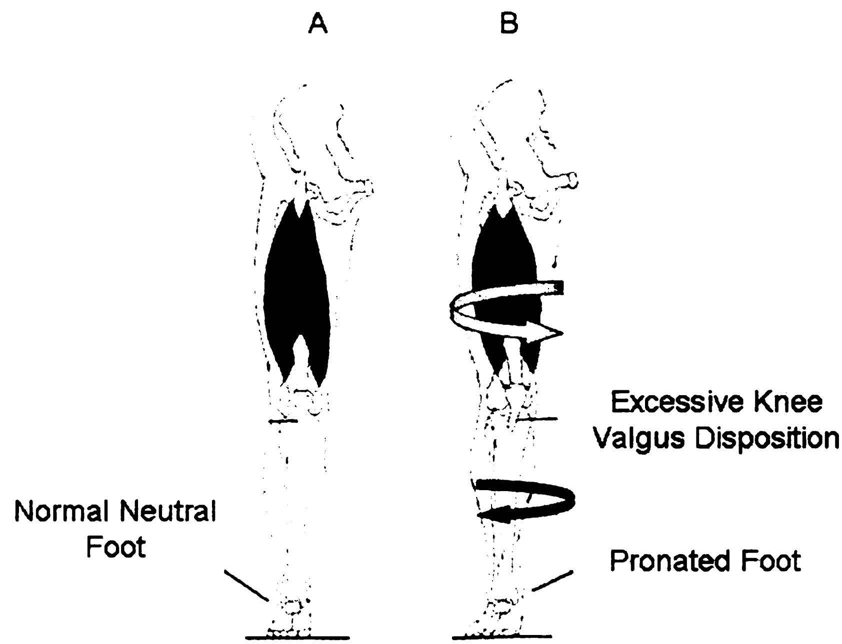

Figure 4. Normal neutral position (A) and the "Position of no return" exhibiting excessive femoral anteversion, external tibial rotation, and concurrent foot pronation (B).

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[4]Retrieved September 1st, 2005 from the World Wide Web: http://www.algeos.com/biomechanics.htm

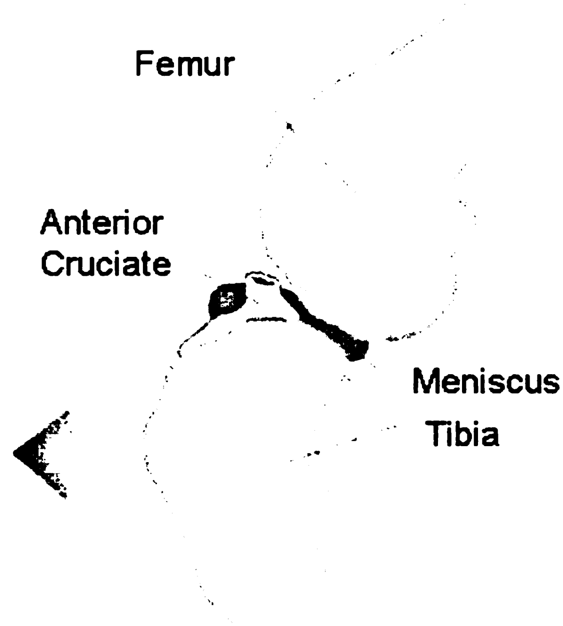

Figure 5. Anterior tibial drawer effect enhances the conditions for partial or complete mechanical failure of the anterior cruciate ligament.

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[5]Retrieved September 1st, 2005 from the World Wide Web: http://www.greatpyrrescue.org/newsletter/aug_03/ fig2.jpg

To further understand these proposed injury mechanisms, it becomes important to identify and observe those potential movements and anatomical, physiological, and environmental factors that are evident when ACL injuries occur. Identifying the conditions that predispose female athletes to ACL injury may assist future investigators and practitioners in the design and implementation of definitive intervention strategies to mitigate the frequency and severity of this type of injury.

Intrinsic and Extrinsic Factors Associated with ACL Injury

Cultural sociologists often consider sport and recreation to be important and vital markers of a growing and thriving culture. Evidence of this phenomenon within the United States is clearly observed by the increasing number of participants that engage in both individual recreational activities and team sports (Huston et al., 2000; McClean et al., 1999). Women, men, and children from a variety of socio-economic backgrounds and levels of individual ability are provided with numerous opportunities to participate in competitive recreational leagues, fitness clubs, community centers, and activity groups.

Associated with an increase in the number of active sport and recreational enthusiasts is a concomitant increase in the number of injuries that result from participation. These injuries occur under a variety of environmental conditions, game circumstances, and etiological factors such as experience, coaching, supervision, playing surface, equipment, and human factors. These variables are typically referred to as "intrinsic" or "extrinsic" factors (Hewett et al., 2006; Huston, et al., 2000).

Intrinsic factors are those factors that include intra-individual characteristics such as growth, maturation, lower-extremity alignment, muscular strength, joint mobility, joint laxity, and hormonal factors. Intrinsic factors are typically difficult to control and may not be modifiable (Harmon & Ireland, 2000). Unlike intrinsic factors, extrinsic factors may be modifiable and include such areas as neuromuscular proficiency, individual motor competence (dexterity), musculoskeletal agonist-antagonist joint-strength ratios, supervision and instruction, playing surface, level of competition, and equipment (Huston et al., 2000).

Although it is generally understood that these intrinsic and extrinsic factors are interdependent, the interactions between physical environment, learning, coaching, physical structure, and the endocrine system are sensitive, unavoidable, and influential on human neuromuscular synergy and ligamentous integrity (Fulkerson & Arendt, 2000; Harmon & Ireland, 2000; Hewett, 2000; Hosea et al., 2000). To further elaborate how these interactions occur, it is necessary to define those special intrinsic and extrinsic factors believed to play a vital role in ACL injury.

Intrinsic Factors

The principle intrinsic factors that have garnered the most attention in the literature concerning ACL injury are skeletal dimorphism and the influence of the endocrine system. Although dimorphism can be misconstrued as a "mal-alignment" of the skeletal structures, it represents that predisposition defined by sex and through the process of normal growth and maturation that distinctly allows the female skeleton to "re-design" itself in preparation for child-bearing (Aiello & Dean, 1999).

Anatomical Factors

Lower extremity skeletal dimorphism provides anatomical configurations that are believed to contribute to the disparity in the incidence of knee injury among female and male athletes (Huston et al., 2000; Fulkerson & Arendt, 2000; Harmon & Ireland, 2000;

Heiderscheit et al., 1999; Neely, 1998; Hvid & Andersen, 1982). However, because there is practically little one can do to alter the process of skeletal dimorphism, intervention with respect to this problem does not present practical solutions for reducing the incidence of ACL injuries among females. Despite the inability to effectively provide practical interventions that can affect the process of skeletal dimorphism, the knowledge and understanding of those skeletal structures, believed to contribute to the primary ACL injury mechanism, is valuable and may provide insight into designing potential intervention protocols that may minimize the ACL injury dilemma.

Because the pelves, femur, and tibia are anatomically and kinetically linked with respect to lower extremity locomotion in activities such as walking, running, jumping, and hopping, these skeletal structures have garnered frequent analysis in research and clinical settings. Typically, the target of these research projects has involved the quadriceps angle (Q-angle), femoral anteversion, and the intercondylar notch of the femur.

Q-angle. The Q-angle is defined as the acute angle between the line connecting the anterior suprailiac spine (ASIS) and the midpoint of the patella, and the line connecting the tibial tuberosity with that same patellar reference point (Figure 6). Various studies have determined the average Q-angle for men and women to range from approximately 8 to 20 degrees, with women having consistently greater Q-angles than men (Huston et al., 2000) . This disparity in measurement is typically attributed to the broader pelves and shorter femurs, more prevalent to the adult female when compared to the adult male (Huston et al., 2000; Neely, 1998).

This Q-angle difference is widely considered the chief contributor for excessive femoral anteversion, genu-valgum (knock-knees), and a resulting external tibial torsion in the female athlete (Neely, 1998). As a result of these three skeletal expressions, there exists the potential to produce greater mechanical stress upon the musculo-tendinous, ligamentous, and articular structures of the lower extremities (Heiderscheit, Hammil, & Van Emmerik, 1998). Thus, the associated mechanical distribution of loading forces on articular structures may eventually lead to abnormal patello-femoral tracking, which may in turn lead to abnormal mechanical compressive, shear, and torsional stresses applied over a smaller joint surface area (Neely, 1998).

The potential exists for these articular structures to be ill prepared for this type of irregular loading, thus pathological conditions such as patello-femoral distress syndrome and chondomalacia may become precursors to ACL and medial collateral ligament (MCL) failure. Chondromalacia is a gradual degeneration of articular cartilage that may play a role in altering walking gait, running gait, and, most important for some sports, the ability to change direction in a mechanically efficient manner under unpredictable circumstances (Heiderscheit, et al., 1999; Huberti & Caves, 1984; Hvid & Andersen, 1982).

Although the magnitude of the Q-angle measure is recognized as generally greater in the adult female when compared to the adult male, there exists strong doubt as to whether there is a positive relationship between Q-angle and knee injury. Several investigations have indicated that the magnitude of the female Q-angle as not significant when normalizing with respect to femoral length (Huston et al., 2000). In addition, it is

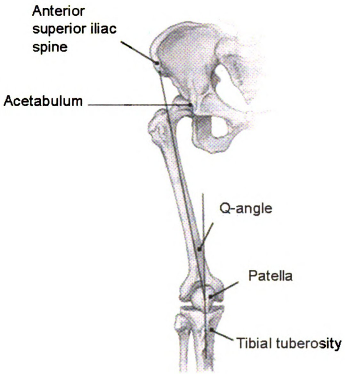

Figure 6. Q-angle.

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[6]Retrieved September 1st, 2005 from the World Wide Web: http://www.steadman-hawkins.com /virtual/education/assets/q_angle.gif

typically emphasized that there are a significant number of female athletic participants that possess high range Q-angle values with no reported lower extremity abnormalities (Hewett, 2000).

An additional problem associated with these measures is the reported unreliability of the various techniques utilized to assess the Q-angle among female and male populations. Nester and France (2001), upon evaluating several reported studies concerning the measurement of the Q-angle, reported extreme variability with respect to the standard deviations of Q-angle measurements due to errors in marker placement on the subjects. Neely (1998) has also found variability in measurement technique leading to poor reliability with regard to Q-angle measures, making it increasingly difficult to derive definite conclusions. Thus, these findings enhance the difficulty with which investigators can relate ACL injury pathology on the basis of Q-angle measurement alone.

Femoral Anteversion. Femoral anteversion is an anatomical condition where the femoral head and neck are rotated anterior to an imaginary line directed through the femoral condyles in the horizontal plane (Figure 7). Average reported values for both males and females are typically in the range of 8 to 18 degrees, with female values on average typically higher when compared to males (Neely, 1998).

Femoral anteversion is considered a precursor to excessive internal rotation at the hip, and is believed to be established through the broadening of the pelvic bones with maturation, resulting with an enhanced Q-angle with greater potential for placing the respective acetabulum (Figure 6) in an anteriorly directed disposition (Neely, 1998; Hvid & Andersen, 1982). Because femoral anteversion restricts external rotation about the hip, the Q-angle has the potential to be enhanced, thus potentially creating a compensatory increase in external tibial torsion, excessive pronation of the feet, and a greater valgus (knock-kneed disposition) effect with weight-bearing. These structural compensations for femoral anteversion are considered optimal because they minimize energy expenditure, via the anteriorly rotating femur and the externally rotated tibia, during locomotion such as walking or running (Fulkerson & Arendt, 2000).

Clinical studies have reported excessive pronation of the foot when the lower extremities are placed into this valgus condition. Excessive pronation is associated with several overuse syndromes, including patello-femoral distress and chondromalacia. These syndromes are typically the result of abnormal mechanical applications of force throughout the patello-femoral and patello-tibial articular structures (Heiderscheit, et al., 1999; Huberti & Caves, 1984; Hvid & Andersen, 1982).

Although femoral anteversion has been linked to lower extremity dysfunction, its role as a primary determinant in non-contact ACL injury is inconclusive. Researchers have been unable to link the reported range of values with acute or chronic knee injuries, particularly because of the evidence that injuries are not necessarily manifested in those with excessive femoral anteversion values (Neely, 1998).

Further difficulty arises when anteversion ranges are associated with an increase in Q-angle value or vice versa. Reports of poor reliability of measured values and highly inaccurate methods of measuring both femoral anteversion and Q-angle have made the association of femoral anteversion as a direct determinant of ACL injury difficult to surmise (Nester, 2001; Neely, 1998).

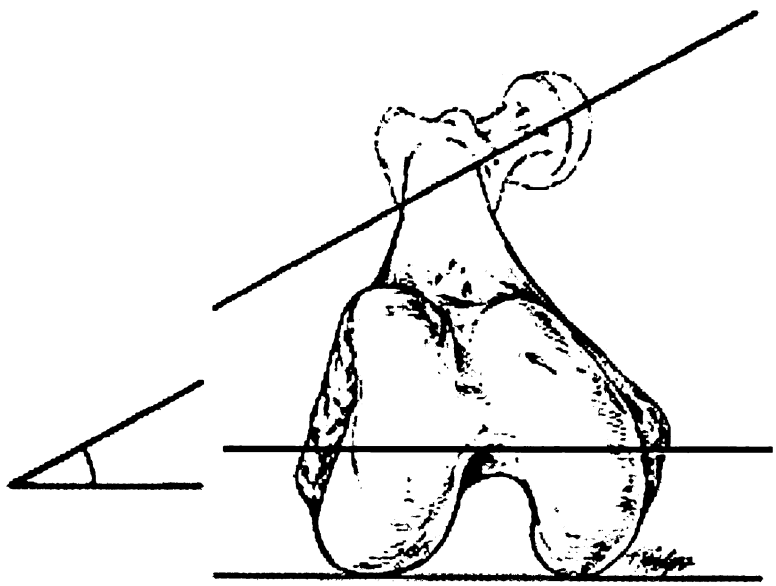

Figure 7. View of the right femur showing femoral anteversion.

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[7]Retrieved September 1st, 2005 from the World Wide Web: http://www.hopkinsmedicine.org/orthopedicsurgery/images/fem_ant.png

Intercondylar Notch Width. Through the use of radiograph a notch width index (NWI), which is a ratio that is determined by comparing the width of the femoral intercondylar notch to the distance between the two distal femoral condyles at the level of the popliteal groove (Figure 8). Several investigations have suggested that there are pathologic relationships among small NWI values (e.g., patello-femoral distress, and acute ACL injury among female athletes), while other investigations have yielded little association between a small NWI measure and ACL injury (Huston et al., 2000; Harmon & Ireland, 2000; Arendt & Dick, 1995).

Much of the association between narrow intercondylar notches and ACL injury stems from the hypothesis that a narrow intercondylar notch is reflective of an ACL that is smaller in diameter with greater risk of mechanical failure versus larger diameter ligaments. Interestingly, notches typically assume an "H", "C", or "A" notch shape with the "A" notch obtaining the narrowest measures (Figure 9). Narrow notches structurally imply a congenitally smaller ACL, which may be more susceptible to chronic and acute stress damage (Huston et al., 2000; Harmon & Ireland, 2000).

Another disadvantage of a smaller ACL ligament is risk of intercondylar impingement. Several studies utilizing cadaver specimens indicate that, during knee joint flexion, it is apparent the ACL will come in contact with the medial margin of the lateral femoral condyle. During extension movements, the ACL may impinge on the anterior intercondylar notch (Neely, 1998).

Despite these findings, attempts to link notch shape and ACL ligament diameter have proven to be inconclusive because many athletes with small NWI's compete at a high level of competition with no history of chronic knee discomfort or acute knee injury

(Neely, 1998). Due to the large range of NWI measures that exist within sexes and the considerable overlap in NWI between genders, many investigators argue it is difficult to conclude that ACL injury is principally derived from this anatomical factor. In addition, there is need to standardize NWI measurements since many of these research investigations have utilized a variety of techniques (i.e., computed tomography, radiographs) at a variety of knee flexion angles to produce conclusions with respect to NWI and notch shape (Arendt & Dick, 1995). The inability to conclude that intercondylar NWI and notch shape are instrumental in ACL ligament failure suggests that it is an anatomical feature that warrants further investigation (Harmon & Ireland, 2000; Hvid & Anderson, 1982).

Summary of Anatomical Factors

The contradictory nature of many studies and a lack of conclusive evidence lend uncertainty to whether or not the lower extremity skeletal structures are a direct mechanism for ACL ligament failure. However, the associations of these intrinsic conditions for both chronic and acute knee injury indicate that these anatomical factors may operate in conjunction with other potential intrinsic and/or extrinsic factors (Hewett et al., 2006; Hewett, 2000; Demont et al., 1999). In spite of this conclusion, there are no practical or non-invasive interventions currently available that could alter normal lower extremity skeletal growth and development. The lack of potential solutions regarding anatomical differences and their contributions to serious knee pathology demonstrate the need to further explore the potential influence of other intrinsic and extrinsic mechanisms that appear to operate in combination with lower extremity alignment.

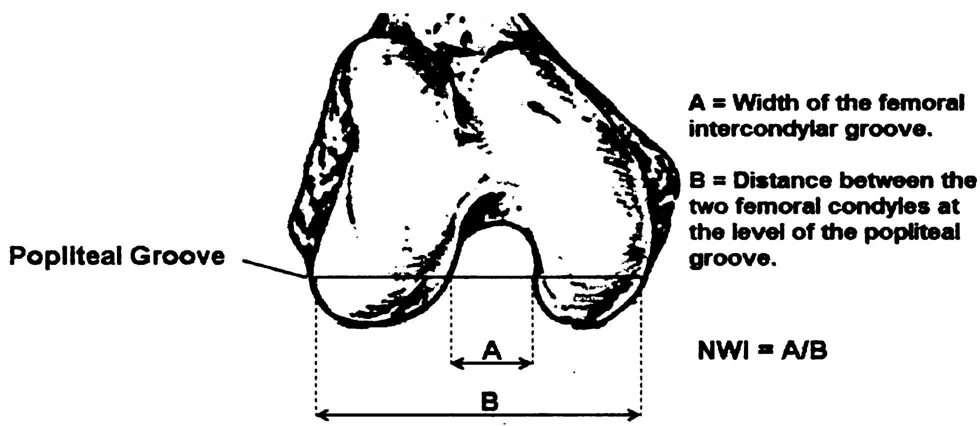

Figure 8. Notch width index (NWI).

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[8]Retrieved September 2nd, 2005 from the World Wide Web: http://orthoinfo.aaos.org/fact/thr_report.cfm?thread_id=157&topcategory=Knee

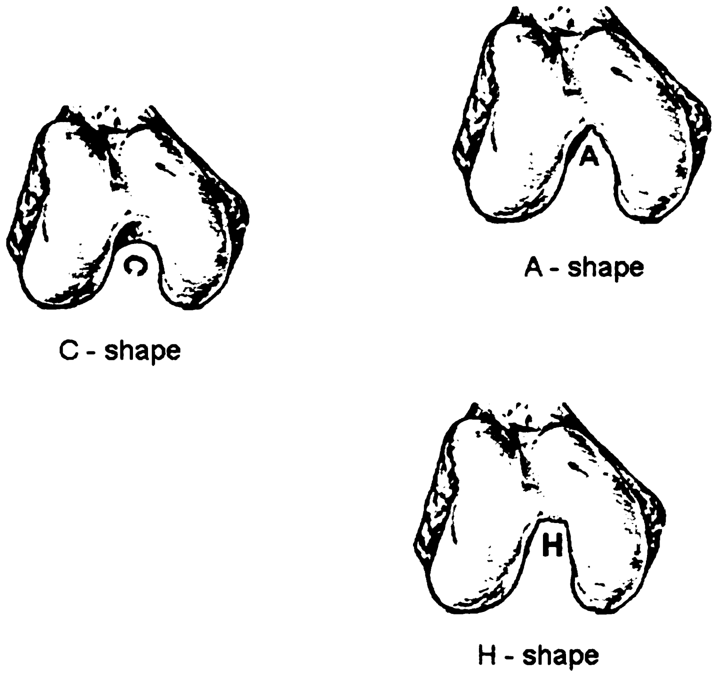

Figure 9. Intercondylar notch shapes.

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[8]Retrieved September 2nd, 2005 from the World Wide Web: http://orthoinfo.aaos.org/fact/thr_report.

cfm?thread_id=157&topcategory=Knee

Hormonal Factors

The menstrual cycle is a physio-endocrine event unique to females with hormonal circulation regulated via the coordinated functioning triad of the hypothalamus, pituitary gland, and ovaries. The duration of the average menstrual cycle is approximately 28 days, but is reported to be quite variable with cycles as short as 20 days and as lengthy as 45 days (Wojtys, Huston, Lindenfield, Hewett, & Greenfield, 1998).

Changes in the female sex steroids that modulate the endocrine events during the menstrual cycle are typically divided into phases that also exhibit variability in time [follicular phase (days 1 to 9), adulatory phase (days 10 to 14), and lacteal phase (days 15 to end of the cycle)]. During the follicular phase, concentrations of both estrogen and progesterone are relatively low. As the cycle progresses toward the adulatory phase, it is preceded by a large surge in estrogen. The lacteal phase follows ovulation with significant increases in both estrogen and progesterone, and then significantly tapers in concentration to the start of the following cycle (Frankovich & Labrum, 2000; Heitz et al., 1999).

Through a variety of endocrinal mechanisms, sex hormones indirectly affect the active and passive stabilization properties of the female musculoskeletal system, notably due to the presence of estrogen and progesterone receptors located in the synoviocytes within the synovial lining of the knee, fibroblasts in the stroma, and cells in the blood vessel walls of the ACL of women (Frankovich & Lebrun, 2000). Sex hormones also play an inhibitory role in fibroblast proliferation and collagen formation, and it is believed that fluctuations in concentration of these sex hormones alter the metabolism of cells in the ACL and in turn influence ligament structure, composition, and integrity (Yu, Panossian, Hatch, Liu, & Finerman, 2001; Huston et al., 2000; Frankovich & Lebrun, 2000; Hewett, 2000; Harmon & Ireland, 2000; Wojtys et al., 1998).

Estrogen has been shown to have measurable effects on the female neuromuscular system with significant changes in contracting and relaxing properties of skeletal muscle, tendon, and ligament strength (Hewett, 2000). Utilizing a knee arthrometer during periods of peak hormonal surges, Heitz et al. (1999) found significant differences in ACL laxity during the follicular and luteal phases of the menstrual cycle, especially through days 10 to 13 of the ovulatory phase. Because the ACL operates in combination with various muscles that cross the knee joint in providing stability, a ligament that exhibits greater laxity will lend less support to the joint and introduce proprioceptive challenges, particularly while undergoing rapid dynamic loading as evidenced during various lower extremity sport actions (Hewett, 2000; Rozzi, Lephart, Gear, & Fu, 1999).

Arendt and Dick (1999) in a review of studies documenting ACL injury occurrence and menstrual cycle activity have found a greater incidence of ACL injury to occur significantly before or after the ovulatory phase of the menstrual cycle. Despite these findings, determining a consistent phase with which ACL injury can be associated has proven to be difficult. In one prospective study over a three-year period, 27 female athletes self-reported within 72 hours the days of their menstrual cycle and provided samples for sex-hormone determination after sustaining an ACL injury. Results of the study concluded 10 of the 27 athletes incurred injury at day one or two of the follicular phase (Slauterbeck, Fuzie, Smith, Clark, Xu, Starch, & Hardy, 2002). In contrast, Wojtys et al. (1998) in a retrospective study utilizing 28 subjects with acute ACL injury over a three month period, found a significant association (29% of all ACL injuries) between ACL injury and the ovulatory phase of the menstrual cycle.

Wojtys et al. (2002) conducted another prospective study with 65 participants over two years in which hormonal assays were conducted within 24 hours of injury and a second assay was conducted within 24 hours of the first day of the menstrual cycle. Forty-three percent or 28 of the 65 subjects incurred an ACL injury during the ovulatory phase while there were 15 and 22 ACL injuries during the follicular and luteal phases, respectively. Although not considered an exclusionary criterion, oral contraceptive use by the participants was also documented for this study. Interestingly, those not taking oral contraceptives were more likely to injure the ACL during the ovulatory phase (N = 24) than during the follicular or luteal phases of the menstrual cycle. Eight of the 14 subjects that utilized oral contraceptives incurred injury during the follicular phase of the menstrual cycle, but no significant effects were discussed with respect to the study. Additionally, the number of subjects utilizing oral contraceptives was relatively low (N=14) and suggests this is a factor that warrants further investigation.

Summary of Hormonal Factors

In light of the suggested indirect association between hormonal mechanisms and ACL injury, studies in this area appear to be inconsistent in defining a specific relationship between ACL injury occurrence and a specific phase of the menstrual cycle. Much of this difficulty stems from the determination of specific serum hormone levels that are considered the definitive gold standard in establishing cycle phase. Inconsistent definitions in menstrual cycle phases contribute to the discrepancies in the findings. Wide circadian variation in hormonal secretion among normal women and discrepancies in the timing of testing also contribute to conflicting results, particularly when a variety of testing methods have been employed (Wojtys, et al., 2002; Frankovich & Lebrun, 2000).

Since hormone stabilization via oral contraception has been implicated as a viable method of altering the tensile properties of the ACL, thus a preventative intervention, it is a proposition that should be further investigated. More research is needed with respect to sample size power, type of contraceptive, chronological age, and factors associated with normal physical growth and maturation.

Extrinsic Factors

Unlike intrinsic factors that are associated with the inherent anatomical and physiological characteristics of an individual, extrinsic factors are related to potentially modifiable traits associated with the type of sport, environmental conditions of the activity, physical conditioning of the athlete, and equipment used (Harmon & Ireland, 2000). Examples of extrinsic factors include neuromuscular proficiency, individual motor competence, musculoskeletal agonist-antagonist joint-strength ratios, quality of supervision and instruction, playing surface, level of competition, and equipment (Hewett et al., 2006; Huston et al., 2000; Harmon & Ireland, 2000).

Because extrinsic factors have the potential to be modified, efforts to address the issue of ACL injury and the gender bias from this perspective are being aggressively pursued in attempting to understand how these factors relate to injury, and, if so, how and when can modification be implemented to attenuate the rate of injuries. Adding further to the dilemma of determining how to intervene is the difficulty of objectively measuring parameters of these extrinsic factors in order to be both appropriate and effective.

Although tangible in concept, instruction can be delivered in a variety of mediums and generate circumstances with varying outcomes. In addition, inadequate financial resources, poor facility maintenance, or a lack of institutional foresight can contribute to the manifestation of playing conditions that are less than desirable or equipment that is aged and inferior in design. The ability to quantify terms like "functional" or "safe" is difficult and often intangible for the injury epidemiologist attempting to control for these abstract concepts while conducting scientific research. As a result, extrinsic factors associated with neuromuscular control represent that area frequently addressed in the investigative literature concerning ACL injury patterns among female athletes.

Muscle Strength and Recruitment

Understanding sex differences and their role in neuromuscular function with respect to the dynamic motion and stabilization of the knee joint appear to be the most rational factors to explain the different rates of ACL injury between males and females (Schultz, Perrin, Adams, Arnold, Gansneder, & Granata, 2001). In concert with this paradigm, there appears to be compelling support for the position that the development of neuromuscular control strategies are essential in providing dynamic joint stability and protection while performing athletic tasks (Withrow et al., 2006; Hewett et al., 2006; Rodacki, Fowler, & Bennett, 2002; Lloyd & Buchanon, 2001; Schultz & Perrin, 1999; Rozzi, et al., 1999; Rosene & Fogarty, 1999; Huston & Wojtys, 1996).

Previous investigations have examined quadricep and hamstring strength to determine if significant differences exist between males and females and further, to determine if significant agonist-antagonist muscular strength discrepancies introduce a predisposing risk for ACL injury. In general, these investigations have concluded that women produce significantly less muscle force in both the quadriceps and hamstrings, even when normalized for body mass (Lephart, Ferris, Riemann, Myers, & Fu, 2002; Huston et al., 2000; Harmon & Ireland, 2000; Huston & Wojtys, 1996).

Because the quadriceps and hamstrings are the dominant musculature surrounding the knee, the strength of these muscles add to the dynamic component of joint stability, thus equalizing articular surface pressure distribution and regulating mechanical complexion (Withrow et al., 2006; Huston et al., 2000). Taking into consideration inadequate muscular strength, weaker musculature may not be able to provide the protective defense necessary to maintain joint integrity and alleviate potentially damaging mechanical loads on the ligamentous structures of the knee under dynamic conditions.

Knee Joint Kinematics and Ground Reaction Forces

Utilizing various kinematic and kinetic data collection techniques, several investigations have provided strong evidence that neuromuscular control of the knee joint while landing from a jump or performing a cutting maneuver on a rigid surface can be appraised through the interpretation of biomechanical variables. As a result, congruent relationships have been established and measured, in particular: angles of knee flexion at impact; time to peak flexion on impact; knee varus, valgus, extension, and flexion moments; peak ground reaction forces; time to peak ground reaction force; and activity of the various musculature of the knee through EMG analyses (Sell, Ferris, Abt, Tsai, Myers, Fu, & Lephart, 2006; Hass, Schick, Chow, Tillman, Brunt, & Cauraugh, 2003; Lephart, Ferris, Riemann, Myers, & Fu, 2002; Besier et al., 2001; McNitt-Gray, Hester, Mathiyakom, & Munkasky, 2001; Colby et al., 2000; McClay, Robinson, Andriacchi, Frederick, Gross, Martin, Valiant, Williams, & Cavanagh, 1994; Devita & Skelly, 1992; Dufek & Bates, 1991; Cross et al., 1989).

Because variant landing and cutting movements are inherent characteristics in many sports, the concomitant effects of ground reaction force (GRF) and measures of knee joint flexion on impact have been implicated as potentially defining the relationship between these contact forces and lower extremity injury (Malinzak, et al., 2001; McClay et al., 1994; DeVita & Skelly, 1992; Dufek & Bates, 1991). In particular, because low angular ranges of knee flexion may induce greater contribution of the quadriceps in producing anterior tibial shear forces, the loads placed on the ACL may be greater and manifest conditions conducive to producing traumatic injury (Withrow et al., 2006; Chappel et al., 2002; An, 2002; Malinzak et al., 2001; Hewett, 2000).

Several investigations have examined knee joint flexion in subjects on impact after landing and cutting to determine relationships between ground contact force and knee flexion. Colby et al. (2000), in a study designed to evaluate the range of knee flexion in subjects during foot strike and subsequent performance of various cutting tasks, obtained a range of values from 14 degrees (stopping) to 29 degrees (cross-cut) of flexion for subjects of both genders. Although no ground reaction force data were collected, the study exhibited the kinematic variability associated with different motor tasks, in this case, cutting maneuvers. As a result, efforts are typically directed toward reinforcing the value of developing biomechanical response strategies under a variety of conditions to help dissipate potentially injurious landing forces (James, Bates, & Dufek, 2003; Hewett, 2001).

Interestingly, the association among ground reaction forces and the range of angles of knee flexion on impact are not always clearly defined. McClean, Lipfert, and Van Den Bogert (2004), in an investigation of intercollegiate males and females performing a sidestep-cutting maneuver, implemented the use of a defensive player or no defensive player to introduce a variable condition and determine the influence of this scenario on various biomechanical parameters of the knee joint. With the defensive player condition, participants demonstrated enhanced ground reaction forces with decreased knee joint flexion on impact, a finding that is in contrast to previous investigations (Malinzak, et al., 2001; McClay et al., 1994; DeVita & Skelly, 1992).

In a previous investigation, McLean et al. (1999) compared knee kinematics among high-level intercollegiate males and females performing a running and cutting task. The investigators did not find significant differences with respect to maximum knee flexion, but did find that maximum flexion in the stance phase, while cutting, occurred significantly later among the males.

Elkhart et al. (2002), in a jump study comparing intercollegiate female athletes to recreational male athletes, found the female athletes to exhibit significantly less mean knee flexion displacement (-17.41° ± 12.96°) than the male controls (-31.10° ± 9.2°), while sustaining ground reaction forces that were not significantly different for both single and double leg landings. In addition to recording the flexion and impact values, time to maximum angular displacement was also determined. The female athletes demonstrated less time to maximum knee flexion (130.04ms ± 71.8ms) when compared to their male counterparts (187.0ms ± 43.98ms). Despite the greater mass values for the male participants (+7.45kg), males appeared to utilize greater flexion at the knee and more time to peak flexion to attenuate the ground contact forces.

In a similar study by Dagenham and Darling (2003), intercollegiate female athletes demonstrated 10 to 14 degrees greater knee flexion and greater knee flexion accelerations than their male counterparts on landing from a maximal height jump under non-fatigued and fatigued conditions. One limitation to this study is the difficulty in ascertaining whether the increased flexion angles and increased knee flexion accelerations are an indicator of the relative strength of the individual or a compensatory motor strategy.

Although ground reaction force data was not collected for the Fagenbaum and Darling study (2003), Bates and Dufek (1991), have expressed that the height of jump plays a minor role with respect to GRF's in comparison to knee joint angle at touchdown and the knee joint flexion angle can be used to reduce the magnitude of impact loads while landing. Thus, it would appear that perhaps the female athletes in the Fagenbaum and Darling (2003) study may have implemented a greater flexion strategy to compensate for other neuromuscular factors that potentially contribute to ACL injury (e.g., latent quadricep-hamstring firing, valgus predisposition).

DeVita and Skelly (1992), studying eight female intercollegiate volleyball and basketball players landing under both soft and stiff conditions, compared ground reaction forces, joint positions, joint moments, and muscle power in the lower extremities. Soft landings averaged 117 degrees of knee flexion versus 77 degrees in the stiff landing, and the mean floor contact phase time (from initial contact until maximum knee flexion) for the female was 152ms versus 342ms for males. During the stiff landings, larger hip and knee extensor moments were observed in addition to larger ground reaction forces, thus demonstrating the knee musculature likely absorbed more energy over time under the soft landing conditions, versus a relatively large force application over a shorter period of time under the stiff conditions.

In concert with the jump investigations of Fagenbaum and Darling (2003), DeVita and Skelly (1992), Bates and Dufek (1991), and Sell et al. (2005) provided evidence that type of jump may play a critical role in defining the magnitude of various biomechanical parameters about the knee. Using multi-directional stop-jump tasks and a vertical jump under reactive conditions, the investigation yielded significant increases in ground reaction force and decreased knee joint flexion on impact, particularly during lateral stop-jump tasks on the side of non-dominant leg and vertical jump. The authors implied the stop-jump task to the non-dominant side required participants to perform a movement that assimilates a side-step cutting maneuver and predisposed them to the "position of no return" as described by Ireland (1999).

Muscles exhibit lengthening which oppose joint flexion during landing and this is reflected as a net joint extensor moment indicative of the muscles role as a shock absorber. Because extensible properties of muscle allow the tissue to absorb much of the impact associated with landing from a jump, flexion on impact is an indicator that force attenuation is taking place (McClay et al., 1994; Devita & Skelly, 1992; Dufek & Bates, 1991). These findings, in concert with those of Lephart et al. (2002) and Malinzak et al. (2001), appear to suggest that the ability to attenuate ground reaction forces on landing from a jump or when performing a cutting maneuver may indeed be associated with neuromuscular capability to devise an appropriate landing strategy. Although stiff landing techniques afford the performer the opportunity to move faster or quickly after initial ground contact, this may occur at the expense of producing potentially greater joint moments and power values which concomitantly can be associated with a greater risk for injury (DeVita & Skelly, 1992).

Knee Joint Extensor Moments

Muscles have a flexion moment arm if they can support/resist an extension knee moment and an extension moment arm if they can support/resist a flexion knee moment (Lloyd & Buchanon, 2001; Hewett, Stroupe, Nance, & Noyes, 1996). Because the muscles of the quadriceps and the hamstrings represent that anatomical constituent responsible for generating moments associated with knee joint stabilization while landing from a jump, the assessment of the flexion and extension moments provide an opportunity to gain insight into the potential for serious ACL injury.

Several investigations have identified net joint extension moments acting eccentrically to oppose knee joint flexion in order to absorb the kinetic energy associated with landing tasks (Chappel et al., 2002; McClay, 1994; DeVita & Skelly, 1992). Chappell et al. (2002), comparing women recreational athletes to male recreational athletes, found women (60.0 ± 5.9kg) to exhibit greater knee extension and valgus moments than the men (76.6 ± 9.5kg) during a three-step jump-stop task for maximal vertical height. Although the values were not significant, the results indicate women may use alternate motor control strategies during landing tasks. In conjunction with these findings, the authors indicated the peak extensor moments were associated and synchronized with peak proximal anterior shear forces at the knee, likely due to decreased angles of knee flexion, increased quadriceps activity, decreased hamstring activity, or a combination of all three conditions.

These conditions are in concert with the findings of Malinzak et al. (2001) who demonstrated intercollegiate recreational female athletes exhibit decreased knee flexion angles on landing, increased muscle quadriceps activation, and decreased hamstrings muscle activation when compared to their male counterparts. Interestingly, these differences may be exacerbated under unstable or unpredictable circumstances such as those typically exhibited under conditions of athletic competition.

These investigations appear to support the proposition that males may employ different neuromuscular mechanisms to compensate for high landing forces than those used by female athletes, especially with respect to the effective balance of opposing joint torques. As a result, mitigating the common occurrence of these events may be an important tool in reducing potential knee injury risk factors since they are characteristics that are pronounced in studies examining ACL injury etiology of the female athlete (Kirkendall & Garrett, 2000; Hewett, 2000; Rosene et al., 1999; Wilk, et al., 1999; Delfico & Garrett, 1998; Cross et al., 1989).

McClay et al. (1994) expressed that there is further concern generated during stiff landings and those jumps that possess greater vertical displacement because of the potential for higher associated extensor joint moments and ground reaction forces that may enhance the intensity and duration of stress to the structures of the knee joint. In a study examining knee joint kinetics associated with landing from a vertical jump, Devita and Skelly (1992) suggested the knee joint extensor moment acts to support the body's center of mass on impact rather than reduce the downward velocity. Thus, the impli

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implication of this action may influence the relationship between ground reaction forces and the knee joint extensor moments, and suggests changes or alterations to the knee joint extensor parameter may modify or attenuate associated ground reactions forces and be important to identify with regard to landing activities.

Summary of the Extrinsic Factors

Upon conducting a review of the pertinent literature, there is compelling evidence to suggest that extrinsic factors are greatly influenced by the neuromuscular control exhibited on the muscles surrounding the knee joint. Because the female athlete appears to demonstrate a more latent response for agonist-antagonist co-contraction, greater extension moment values on impact, less knee joint flexion on impact, and faster times to peak flexion when landing from a jump or performing a cutting maneuver, these measures enhance the potential for higher associated peak GRF's and thus, the potential for serious ACL injury (Hewett, 2000; Hewett et al., 1996; Dufek & Bates, 1991).

Devita and Skelly (1992) have emphasized that in order for muscle to effectively contribute in the dissipation of kinetic energy, it requires not only greater angles of flexion on impact, but more time to peak flexion. Lephart et al. (2001) concurred with this position in supporting the notion that peak flexion angle on impact and time to peak flexion angle become valuable indicators of the ability to attenuate GRF's from a landing or cutting maneuver.

The muscles and ligaments surrounding the knee control how the total joint force is shared between the articular surfaces of the femur and the tibia, and it is recognized that the ligaments of the knee become more taut when the knee is in more extended postures. Because of the ACL's role in restraining anterior tibial translation, poor

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neuromuscular synchronization between the secure compression effects of quadricep/hamstring co-contraction can create an environment of decreased functional knee joint stability and open to potential ACL injury when landing from a jump or conducting a cutting maneuver. There is further concern when the temporal characteristics of the peak forces are occurring earlier, rather than later in landing, indicating potentially dangerous forces need to be managed throughout the cycle of landing and/or cutting (Dufek & Bates, 1991). Upon reviewing the literature, men appear to be spending a greater percentage of stance time eccentrically loading the quadriceps, thus, perhaps spending more time controlling and stabilizing knee joint motion before the generation of axial torques, when compared to women (McLean et al., 1999).

Interestingly, males experience higher impact forces from landing, yet suffer fewer injuries. This may indeed be related to their ability to decrease the extension, adduction, and abduction moments when making impact with the ground surface. Thus, the ability to coordinate proper landing strategies in order to initiate protective neuromuscular defense mechanisms that provide functional joint stability under dynamic conditions appears to be an effective protocol for the male athlete to reduce the potential for risk of serious knee injury (Huston et al., 2000).

Collectively from a research perspective, it is apparent that efforts to initiate changes of the neuromuscular parameters among female athletes must begin with understanding how the nervous system controls muscular dynamics in devising compensatory strategies to help attenuate those GRF's and neuro-mechanical characteristics that may contribute to the ACL injury dilemma.

Functional Joint Stability, Muscle Stiffness, and Kinesthesia

Although motor control is an area of study that is exhaustively scrutinized, there exists a great body of information that remains both inconclusive and elusive with respect to how the central nervous system (CNS) specifically dictates normal limb function and locomotion. Despite these shortcomings, essential tenets of neurophysiology are established from which a basic understanding of neural mechanisms that control muscle contraction under dynamic conditions exists.

Neuromuscular control is a term associated with the field of motor control, and is used to reference those numerous and elaborate mechanisms that comprise the nervous system and delineate their role in voluntary, involuntary, and reflexive muscle activation (Lephart & Riemann, 2002a). Proprioception is defined as the culmination of all neural inputs originating from the visual apparatus, vestibular system, and peripheral mechanoreceptors (Hamill & Knutzen, 2003). The role of the peripheral mechanoreceptors is to transform mechanical distortion (e.g., changes in joint position, muscle length, or muscle tension) into an action potential that enters the spinal cord and ultimately regulates reflexes and motor control (Hamill & Knutzen, 2003; Latash, 1998).

Sources of these joint proprioceptive inputs are located throughout various structures of the body including articulations, tendons, muscles, inner ear, and both cutaneous and deep tissues. The regulation of this interaction between the sensory (afferent) and motor (efferent) pathways is complex and is commonly referred to as the sensorimotor system (Hewett, 2002). Those components associated with the sensorimotor system that contribute to dynamic joint stability are part of a larger domain that is synonymous with those areas that dictate whole-body motor control. Thus, it is generally understood that effective motor control is dependent upon accurate sensory information concerning both the external and environmental conditions of the body (Lephart & Riemann, 2002b).

Kinesthesia is a term that is often mislabeled synonymously with proprioception. It is dependent upon sensorimotor activity and specifically, proprioceptive input. Thus, kinesthesia is defined as knowledge of the position and orientation of a body segment in space or its relative position in reference to another body segment (Latash, 1998). At a basic level, kinesthesia allows individuals to conduct gross and precise movements without the reliance of visual control, perform motor tasks that require multiple-limb coordination, and adjust motor patterns with respect to the force field in which they move (Latash, 1998).

The acquisition of functional knee joint stability is dependent upon components of the human anatomical complex to be both pliable and versatile for various task capabilities during locomotion. These components are typically classified as either passive or dynamic restraint components. The passive components consist of the ligamentous structures, joint capsules, cartilage, and the bony geometry about the articulation, while the dynamic restraints are those components that comprise the feed forward and feedback neural inputs (e.g., muscle spindles, golgi tendon organs) to the skeletal muscles that literally cross an articulation (Lephart & Riemann, 2002a).

Feed forward control is considered to describe actions occurring upon the identification of the beginning, as well as the effects of an impending stimulus or event, often referred to as an anticipatory action (Hewett, 2000). Feedback is a term used to describe actions occurring in response to the sensory detection of direct effects from the arrival of a stimulus or stimuli to the system, and is largely influenced by previous experiences with a detected stimulus (Lephart & Riemann, 2002a; Enoka, 1994).

In the static state, the ACL provides restraint to anterior tibial translation with respect to the femur. However, forces incurred at the joint during dynamic conditions, such as those realized in sport, may be beyond the functional restraint capacity of the passive qualities of the ACL. As a result, the neural recruitment of muscular forces via an optimal interaction between the passive and active restraint systems becomes essential in maintaining functional knee joint integrity (Pollard, Heiderscheit, Van Emmerick, & Hamill, 2005; Huston & Wojtys, 2001).

Under normal neurophysiologic conditions, the neuromuscular system interacts with sensory feedback from the ligament structures, muscle activity, and the joint surface contact forces to provide essential joint stability for protection (Lephart & Riemann, 2001; Schultz & Perrin, 1999). One of the vital factors associated with producing functional joint stability during activity is the reliance on neuromuscular control to enhance and dictate the property of muscle stiffness. If increased muscle stiffness exists, then there is increased joint stiffness, thus, greater potential to prevent the incidence of joint subluxation via ligamentous damage under those conditions that involve circumstances of dynamic loading (Lephart & Riemann, 2001).

Lephart and Riemann (2001) have defined muscle stiffness as the ratio of change in applied force per change in length of the muscle, and have expressed the existence of three factors associated with this property - passive, intrinsic, and extrinsic. Passive factors originate from the viscoelastic contributions of the non-contractile elements of the muscle, while intrinsic factors are comprised of any number of actin-myosin crossbridges existing at a given time. Reflexes comprise the third factor and contribute to muscle stiffness via the elongation of the muscle-tendon unit.

Neuromuscular control of knee stability, and specifically muscle stiffness, is established through both reactive (reflexive) and intentional (preparative) responses that are mediated by proprioceptive feed forward and feedback mechanisms (Schultz et al., 2001). Like muscle stiffness, kinesthesia or position sense is dependent upon the various peripheral receptors (e.g., mechanoreceptors) from which the degree of activation is reliant upon muscle length, velocity, force, joint angle, and pressure on cutaneous receptors.

Thus, it can be affirmed that both muscle stiffness and kinesthesia are motor byproducts in response to proprioceptive stimuli and, in essence, complete a "loop" within the sensorimotor system. The specific mechanisms that regulate these neural mechanisms under a variety of physiological conditions are voluminous and have been described in intricate detail elsewhere within the literature (Hewett, Paterno, & Myer, 2002; Lephart & Riemann, 2002b; Lephart & Riemman, 2001; Latash, 1998; Enoka, 1994; Crago, Lemay, & Liu, 1990; Denier van der Gon, Coolen, Erkelens, & Jonker, 1990).

Neuromuscular Intervention

Differing sex-derived anatomical characteristics and the ethical difficulty of prescribing oral contraceptives to mitigate ligament laxity have led a significant number of investigators to suggest that the most direct methods of ACL injury intervention involve the alteration of neuromuscular function. Because proprioceptive inputs define the regulation of the dynamic restraint components, and specifically, properties of muscle stiffness and kinesthesia, physical training protocols have been devised as a means of potentially altering particular biomechanical parameters associated with ACL injury in sport (Mandelbaum, Silvers, Watanabe, Knarr, Thomas, Griffin, Kirkendall, & Garrett, 2005; Myer, Ford, Palumbo, & Hewett, 2005; Noyes, Barber-Westin, Fleckenstein, Walsh, & West, 2005; Irmischer, Harris, Pfeiffer, DeBeliso, Adams, & Shea, 2004; Hewett et al., 2002).

Determining the effectiveness of a physical training protocol on altering landing strategy should include the ability to assess those biomechanical parameters that represent an output function of the dynamic joint stabilizing factors (e.g., joint moments, joint kinematics, muscle myography, and ground reaction forces). Quantification of these parameters during locomotion enable the investigator to surmise the mechanical contributions of muscle fibers, ultimately determined by sequences of activity patterns generated by the CNS (Denier van der Gon, Coolen, Erkelens, & Jonker, 1990; Crago, Lemay, Liu, 1990; Brooke & McIlroy, 1990).

Previous investigations have demonstrated the potential to alter the various proprioceptive feed forward and feedback mechanisms associated with control of the lower extremity segments during the performance of various athletic maneuvers (Cerulli et al., 2001; Hewett et al., 1996; Wojtys et al., 1996). Rodacki et al. (2002) and Heiderscheit et al. (1998) have suggested that control organization occurs only after a period of practice where the subjects are allowed to repeatedly solve the task requirements and learn how to alter their muscle properties to improve a motor task. As skill is acquired, variability within the activity is decreased because the CNS selects an optimal pattern with which to achieve motor efficiency. Thus, it would appear that sensorimotor accommodation and adaptation, in conjunction with CNS pre-planning, are likely to provide neural recognition and muscular responses that inevitably create motor programs or "engrams" that work to correct potential motor control error that may contribute to injurious circumstances (Hewett, 2002; Cerulli et al., 2001).

For neuromuscular response modification to occur in sport, the injury mechanism or pattern of movement must be recognized by the sensorimotor system as potentially debilitating. The corrective response is then initiated to modify the movement of the involved limbs in a way that reduces or alters the stresses applied to the joint and supporting ligaments, by ordering a different movement or reflexive strategies that alleviate potentially damaging trauma to local structures. This strategy implies that an altered neuromuscular response is one method to change a movement pattern and to modify the internal forces applied to the system. An appropriate alteration of muscle activation patterns may provide protection to those structures that are at the highest potential for injury (Cerulli et al., 2001).

Hewett et al. (1996) examined the effect of a jump-training intervention program on landing mechanics and lower extremity strength among high school female volleyball players. The jump-training program was designed to decrease landing forces by teaching neuromuscular control of the lower limb while performing a landing task. After training, peak landing forces decreased 22% and knee adduction and abduction moments decreased approximately 50%. In conjunction with resistance training, athletes were trained for six weeks on jumping and landing techniques and how to utilize key verbal cues (e.g., "on your toes", "light as a feather", and "recoil like a spring") to help them visualize particular phases of the jump.

Similar in structure to the Hewett et al. (1996) protocol, Hewett, Riccobene, and Lindenfield (2001) introduced another six week three phase intervention protocol labeled "sportmetrics" that included stretching, plyometrics, and selected progressive resistance training exercises. Twelve hundred sixty-three athletes representing 43 soccer, volleyball, and basketball teams from 12 high schools participated in the study. Three hundred sixty-six female athletes followed the intervention protocol while 463 females and 434 males served as controls. Of the athletes participating in the study, ten of the untrained females, two of the trained females, and two male athletes sustained serious knee injury during their respective competition periods. Although the study was limited by relatively low injury numbers (five non-contact ACL injuries and five medial collateral ligament (MCL) injuries were sustained by the untrained female athletes, while no trained female athletes and one male athlete reported an ACL injury), the prospective study demonstrated a decrease in serious knee injuries among those participating in a neuromuscular intervention program.

Wojtys et al. (1996) implemented a six week intervention program that included placing adult volunteers into isokinetic strength, isotonic strength, agility, or control groups to test the effects of training on muscle reaction time after an unanticipated perturbation to the knee. The agility group significantly improved spinal reflex times of the lateral and medial quadriceps, and the cortical response times of the gastrocnemius, medial hamstrings, and medial quadriceps. The isokinetic training group significantly produced lower response times after the training period and the isotonic group's response times did not significantly change. The investigators concluded that isotonic and isokinetic strength training of the lower extremities did not appear to enhance muscle response time, whereas agility exercises presented the potential for success with this parameter.

Movement Competence

Movement in the sport context often exists in a constant flux of emotional, tactical, and physical indeterminate variability and unpredictability. Thus, in order to "prepare" for indeterminate variability, it would appear sensible to introduce tactics and intervention techniques that assimilate as close as possible those indeterminate movement conditions observed in practice and in competition. For validity purposes, the more closely the patterns of movement utilized in an intervention resemble what occurs under competitive conditions, the better the investigator should be able to ascertain how altered proprioceptive inputs affect motor strategy, irrespective of the motor task.

Sell et al. (2005), Hewett et al. (2002), and Hewett (2002) have suggested the enhancement of proprioceptive function requires coaching personnel to expose athletes to "high-risk" maneuvers in a "controlled" or supervised environment. The authors do not clearly delineate the term "high-risk". However it is expressed that the intent of these activities is to facilitate the development of multi-joint neuromuscular engrams that combine joint stabilization, acceleration, deceleration, and kinesthesia through intermittent protocols that progress from low-intensity simple unidirectional movement patterns to complex multi-planar patterns of movement.

Besier, Lloyd, Ackland, and Cochrane (2001) have proposed the use of drills that include unexpected or "unanticipated" maneuvers that can potentially refine the neurophysiologic processes through which the CNS dictates movement. The authors imply that familiarization in performing unanticipated rapid changes in direction rather than preplanned motions directs the CNS to initiate the appropriate adjustments that may reduce response times to the visual and mechanical stimuli experienced in competitive sport and physical activity.

Recommendations may include, but are not limited to, initiating balance perturbations, alternating upper extremity and lower extremity movements simultaneously, single-leg plyometric activities, and/or rapidly changing directions (Hewett et. al, 2002). Rapid unplanned changes in direction under unpredictable circumstances often occur frequently during competitive and practice scenarios among popular American sports (e.g., basketball, volleyball, and soccer).

To date, few published works exist that have examined biomechanical parameters of the knee joint of subjects performing unanticipated changes in direction of movement. Besier et al. (2001) examined lower limb kinematics and kinetics of 11 healthy male soccer players who performed cutting maneuvers under both preplanned and unanticipated conditions. Results of the study determined that performing a sidestep cut under unanticipated conditions increased external valgus moments 1.5 to 12.3 times the magnitude of the preplanned conditions. When comparing unanticipated conditions to preplanned, internal rotation moments and knee flexion angles were significantly higher during the pushoff phase and external rotation moments were significantly higher during all stance phases of the cutting task. These results suggest that changes in the movement characteristics (e.g., deceleration, cutting angles, posture, and center of gravity) during an unanticipated task may be concomitant with the altered execution of a motor task, thus the potential for increased external loads applied to the knee joint when compared to the preplanned conditions.

Myer et al. (2005) examined the effects of a comprehensive six week neuromuscular intervention program on measures of performance and lower-extremity movement biomechanics among adolescent female athletes 15.3 ± 0.9 years of age. Participants within the experimental group demonstrated increases in knee flexion-extension range of motion during the landing phase of box jumps, along with concomitant decreases in valgus and varus torques. The investigators implemented an unanticipated directional cutting maneuver but did not disclose the specific length of the run or the angle of cut by the subject upon receiving the directional cutting cue. Dependent upon the study design and execution of the experiment, these factors may actually reveal anticipatory influence with regard to the running and cutting task by inducing deceleration, or angles of cutting that exhibit an "arc-like" pattern as opposed to an angular disposition. Consequently, it is possible the biomechanical parameters collected in the laboratory setting may not be comparable to those conditions encountered in competition or practice.

Cowling and Steele (2001), utilizing EMG, examined muscle burst activity of the thigh musculature and gastrocnemius during an unanticipated-catch or no-catching task among their subjects who landed from a jump-task associated with netball. Although ground reaction forces were similar in magnitude for both conditions, muscle burst onset of the quadriceps and gastrocnemius were significantly earlier when compared to the biceps femoris during the unanticipated-catch conditions.

Besier, Lloyd, and Ackland (2003), comparing unanticipated run-and-cut maneuvers to straight ahead running, found significantly greater muscle activity in the lower extremity during the cutting maneuvers. The enhanced muscle activities coincided with the higher internal and external rotation moments exhibited during the sidestep cut. Additionally, there was an increase in muscle activity prior to heel strike in the straight ahead run, suggesting a pre-programmed neuromuscular response in anticipation of impact with the ground.

Further evidence of lower extremity muscle pre-activity prior to impact with the ground is in concert with the findings of Neptune et al. (1999). Utilizing EMG, significant muscle "burst" activity of the knee flexors and extensors was evident prior to foot contact in ten recreationally active males who performed various sidestep cutting and v-cut maneuvers.

Investigations by Besier et al. (2001), Cowling and Steele (2001), Neptune et al. (1999), and Brooke and McIlroy (1990) appear to support the premise that muscle activation strategies may be coordinated to help stabilize the knee joint and other supportive structures prior to impact with the ground during running and other associated athletic maneuvers. With respect to ACL injury and the knee, Besier, Lloyd, Cochrane, and Ackland (2001) have expressed that when potentially destabilizing forces threaten the integrity of the anatomical structures, the CNS is capable of adjusting muscle activation patterns to counter the large flexion loads to the knee muscles surrounding the joint and additionally, must apply a large extension moment that may result in a net anterior force to the tibia when the knee is near full extension. This mechanical predisposition is thought to be a chief requisite for serious ACL injury (Lephart et al., 2002b; Colby et al., 2000).

Training for Dexterity

In the context of human movement, dexterity is defined as that ability of the nervous system to develop a quick and simple motor solution to a motor problem (Bernstein, 1996). To be dexterous does not propose that an individual perform harmonious, coordinated movement patterns. Instead, the efficiency or resourcefulness of movement is dependent upon the ability to predict the possible changes in the external environment or changing conditions and to correspondingly plan movements.

In the analysis of movement, both qualitative and quantitative characteristics are represented with respect to the completion of a motor task. The qualitative characteristics are established when the movement does what is required or achieves "correctness", while sensory corrections or, the precision of movement can be assessed if quantitative (biomechanical) characteristics can be evaluated. Because sport, in practice and competition, frequently provides a venue of variant motor abundance under both anticipated and unanticipated conditions, the enhancement of sensorimotor acuity from the practice of a number of different motor skills provides an opportunity to form an important background for dexterity (Bernstein, 1996).

Several investigations have assessed the effectiveness or influence of a neuromuscular intervention program on biomechanical parameters of the knee joint among subjects performing athletic-type maneuvers (Sell et al., 2006; Myer, et al., 2005; Irmischer et al., 2004; Cowling & Steele, 2001; Hewett et al., 2001; Hewett et al., 1996). These various protocols have been introduced under the premise that sensorimotor adaptations that take place dependent upon the stimuli the proprioceptors receive during or prior to an anticipated motor task or demand. The results of these studies appear to demonstrate the potential influence that intervention programs have on altering particular biomechanical parameters (e.g., ground reaction forces, joint moments, and/or angles of knee flexion on landing), and add to the notion that efficient neuromuscular control is essential to dynamic joint stability and provides a baseline of information that may lead to undermining the problem of ACL injury among female athletes (Schultz & Perrin, 1999).

Although basketball athletes routinely land from jumps of varying heights and demonstrate changes in direction at a variety of speeds, it is believed the non-contact nature of the ACL injury is exacerbated under those conditions where there is insufficient time to prepare for the athletic maneuver, thus limiting response and/or introducing inappropriate postural adjustments and the inability to generate muscle activation patterns suitable for joint stabilization. Considering these circumstances, could the establishment of "dexterity" at this juncture (i.e., between landing and subsequent change in direction) provide a scenario whereby the athlete must learn to provide an immediate motor solution to the motor problem? Is this form of motor learning best established under those training conditions that introduce precepts of dexterity? Finally, perhaps of most importance, if enhancing dexterity establishes the alteration of those biomechanical parameters associated with ACL injury, is there an appropriate physical developmental stage (e.g., childhood, adolescence, and young adulthood) when an intervention should be implemented?

Determining when to intervene is particularly difficult to ascertain because few studies have compared pre-pubescent to post pubescent female athletes, and in general, studies involving the observation of biomechanical parameters of the knee among adolescent female athletes are sparse. While examining kinematic and kinetic parameters of lateral, static, and vertical landing sequences among recreationally active pre-pubescent (mean age 9.0 ± 1.0 yrs) and post pubescent (20.2 ± 1.2 yrs) female athletes, Hass, Schick, Chow, Tillman, Brunt, and Cauraugh (2005) found the pre-pubescent group to land in a position of approximately 4.5 degrees greater knee flexion, albeit exhibited greater knee extension moments and significantly greater ground reaction forces. One major limitation of this particular study was that no maturational assessment was conducted among the participants of the pre-pubescent group. This is a concern because there is the underlying implication that the anatomical and physiological changes associated with the onset of puberty may play a role in altering neuromuscular control; thus, further research utilizing maturational assessment among adolescent female athletes is warranted.

In an effort to alter neuromuscular function and mitigate the incidence of ACL injury among athletic populations, the implementation of unexpected or unanticipated movements has been suggested by Besier et al. (2001), and controlled high-risk movements have been recommended by Hewett (2002) and Hewett et al. (2002). Although none of the aforementioned papers provided specific exercise criteria, these training applications appear to be in concert with Bernstein's (1996) premise that selecting and implementing those special exercises and activities that enhance dexterity become fitting, provided that they include those motor skills and sequences that introduce an element of unpredictability, which inevitably through training, become predictable or "manageable". In essence, the purpose of dexterity training is to enhance the opportunity for the sensory organs to increase their sensitivity during the practice of an athletic task of significant importance.

Because the qualitative and quantitative characteristics of a motor task are subject to the influence of practice, the precision of movement has high potential for improvement and identifying this form of accuracy may demonstrate some transfer of "exercisability" (Bernstein, 1996). As a result, dexterity training may be an effective means of acquiring preferable angles of knee flexion on impact and further, non-reflex muscles can be pre-programmed or "trained" to increase the joint range of motion values, thus reducing the potential for risk of serious knee injury.

Using Bernstein's (1996) proposed definition, it is apparent that dexterity training programs can be ambiguously created to resemble a category of "exercisability" that possesses distinct features of unpredictability that require the trainee to produce motor "solutions". Previous interventions including those of Mandelbaum et al. (2005), Myer et al. (2005), Hewett et al. (2001), Wojtys et al. (1996), and Hewett et al. (1996) have utilized a variety of methods with which to intervene, thus adding to the difficulty of deciding which exercises are the best to prevent or mitigate ACL injury. Further, in what sequence should these exercises be implemented and for what period of time? How frequent should this form of intervention be administered?

Because previous investigations have encountered difficulty with compliance, standardization, or randomization of subjects (Cowling & Steele, 2001; Hewett et al., 2001; Hewett et al., 1996), it becomes vital to gain greater insight into the application of these injury intervention programs. In particular, the adolescent female athlete is a specific at-risk population at variable stages of maturation that necessitates further research that includes some method of maturational assessment and an opportunity to investigate the effects of training interventions that include those unanticipated motor characteristics inherent and prevalent in sport.

CHAPTER 3

METHODS

Experimental Design

To test the research hypotheses, a test-retest quasi-experimental design study was employed. Coaches of Under 14 (years) Amateur Athletic Union (AAU) female basketball teams were informed of the study through a Michigan AAU Basketball internet website forum (www.miaaugirlsbb.com) and posting. The coaches were solicited to determine if they would be interested in providing their team as either an experimental or control group for a study investigating the effects of a dexterity training protocol on biomechanical parameters of the knee joint associated with landing from a maximal vertical jump task.

The dependent variables assessed for both groups included the following: peak ground reaction force (PGRF), peak knee joint flexion (PKJF), time to peak knee joint flexion (TKJF), and the peak knee extension moment (PKJM). The independent variable (treatment) for this study was a twice-per-week, six week dexterity training intervention administered to the experimental group, and conducted in a manner that did not detract from the allotted time for basketball skill training and scrimmage. The control group was not exposed to any intervention other than those skills and tasks expected during normal basketball practice and competition.

Participants

Upon approval of the project through the University Committee on Research Involving Human Subjects (UCRIHS), female athletes from two youth female basketball teams were selected on a first-come, first-serve basis, from a pool of competitive teams participating as members of the AAU within the state of Michigan. The AAU is the premier competitive environment for female adolescent basketball athletes within the United States. Participants typically demonstrate specific basketball skills and exhibit fitness parameters considered superior for their respective age groupings. The criteria for participation in the study were female, between the chronological ages of 13.0 to 14.99 years, and no previous history of knee joint injury. For this study, pertinent subject characteristics are presented in Table 1.

Completion of the study was reliant upon four scheduled sessions with each participating team, excluding those contacts associated with the administration of the intervention protocol to the experimental group. These four scheduled sessions were identified as: parent/participant informative practice session, anthropometric/vertical jump session, pre-intervention data collection session, and the post intervention data collection session. After the initial parent/participant informative session, the team within the closet geographical proximity to the research institution was selected to serve as the experimental group, while the team with the furthest geographical proximity was selected to serve as the controls. Compliance for pre- and post intervention participation was 100% for all participants that comprised the experimental group. One member of the control group could not complete the post intervention data collection session due to scheduling conflicts, and was excluded from the study. This resulted in four participants for the experimental group and two participants for the control group.

Table 1

Participant Anthropometric Characteristics and Maturity Status

Subject Identification	*Age (yr)*	*Height (m)*	*Mass (kg)*	*Maturity Status (% of predicted adult stature)*
E1	13.4	1.57	55.5	97.06
E2	13.5	1.68	51.5	97.23
E3	13.9	1.65	49.8	97.61
E4	14.2	1.75	85.4	101.15
C1	14.3	1.74	83.9	100.33
C2	13.4	1.56	50.2	96.55

Note. E = experimental group.
C = control group.

Session 1: Parent/Participant Informative Practice Session

To accommodate parent and guardian concerns with respect to the methodology, instrumentation, potential risks, and benefits of the study, an introductory parent and athlete meeting was conducted at a regularly scheduled practice session to inform all participants of the higher incidence of ACL injury among female athletes when compared to their male counterparts for the sport of basketball. In addition, the scope and design of the study was explained in detail and the athletes were asked if they would like to voluntarily participate in a study whose aim is to gain greater understanding of how a dexterity training program may alter biomechanical parameters associated with the knee joint. After completion of the informational session, form for youth assent for the participants and informed consents for the parents or legal guardians were distributed (Appendix A). Upon reviewing the youth assent and consent documents, those parents, guardians, and athletes interested in participating in the study submitted signed forms to the research team.

Session 2: Anthropometric/Vertical Jump Session

Prior to the collection of pre-intervention data, all pertinent anthropometric data was acquired at a scheduled practice session. Body mass was measured on a standard scale (Measurement Specialties, Fairfield, NJ, USA) while subjects wore athletic shorts, t-shirt, and socks. To derive estimates of the segment masses, segment moments of inertia, and segment joint centers, standing height was obtained with the use of a standard anthropometer (Siber - Hegner & Company, Zurich, Switzerland) and segmental lengths for the right thigh, right shank, and right foot were acquired with a standardized procedure described by Lohman, Roche, and Martorell (1988).

Maturity Assessment

The purpose of the maturity assessment was to estimate maturity status and percent of adult attained height of the subject population because individuals closer to their predicted adult stature than would be expected for their age and gender are associated with advanced maturational status. In addition, assessment of maturity status contributes to a broader body of knowledge that may be utilized in future studies with respect to the descriptive characteristics of this subject population.

For this project, two self-report items were used to assess the stature of the biological parents. Parents of the participants were asked to report their stature in feet and inches and these values were subsequently converted to centimeters. The self-reported stature of each parent was adjusted for overestimation using an equation developed from over 1000 measured and estimated heights of subjects (Epstein, Valoski, Kalarchian, & McCurley, 1995).

The Khamis-Roche (1994) method is a procedure of predicting adult stature without using skeletal age, and, is a non-invasive maturity assessment technique that utilizes linear regressions of mid-parent stature (the average height of the two parents) and current values of participant stature and weight. These values were determined to provide an estimate of percentage of adult height attained upon which a biological maturity rating was established. An underlying assumption by Khamis and Roche (1994), while predicting adult stature, is that individuals closer to their predicted height than would be expected for their age and gender are generally advanced in their maturational status. Thus, two participants of the same chronological age can be of the same height, but one may be biologically closer to adult height than the other. The individual that is biologically closer to adult height is considered advanced in maturity status compared to the individual who is further removed from predicted adult height (Malina & Bouchard, 1991). For example, the mean percentage of adult stature attained in girls at age 12 years is 92.61% (Bayer & Bayley, 1959). Thus, a girl who attained 95% of her predicted adult stature at the age of 12 years would be considered advanced in her maturity status.

Vertical Jump Test

In order to collect and standardize kinematic and kinetic data of the subjects in their performance of a jump task, it was necessary to assess the maximal vertical jump for all participants with the use of a Vertec™ (Sports Imports, Columbus, OH) device. Each subject's maximal vertical jump height was calculated by subtracting their standing reach from the jump height attained during a maximal jump and reach effort. After observing a demonstration on how the Vertec™ device is correctly used, each subject was provided the opportunity to practice several jump and reach trials. Upon familiarization with the instrument, standing reach was assessed by having the participant stand with feet parallel and directly underneath the acrylic vanes of the Vertec™ device. The subject was then asked to extend the dominant arm as high as possible overhead without having any portion of her feet leave the surface of the floor. With the dominant arm extended completely overhead, each participant was instructed to push away as many acrylic vanes as possible until a maximal reach height was assessed and recorded (Figure 10).

After the standing reach value was acquired for each athlete, the reset pole of the Vertec™ device was adjusted to a height from which a challenging vertical jump attempt could be performed. While no attempt was made to alter each subject's individual jumping style, subjects were provided three trials to execute a maximum vertical jump effort by tapping the acrylic vanes at the apex of each jump effort. The highest attained jump effort was then assessed and recorded. Maximum vertical jump height was then calculated by subtracting the standing reach value from the highest assessed jump effort of the three maximal jump efforts and the resulting figure was then recorded as the participant's maximal vertical jump height.

To control for potential learning effects, the jumping and landing protocol used for this study was introduced prior to any kinematic and kinetic data collection. The jump task protocol required the athlete to conduct a maximal effort vertical jump, tap the acrylic vanes of the Vertec™ device, land, and sprint two meters either to the right or to the left as instructed by the investigator. This landing and sprinting procedure was repeated three times in both directions for all participants.

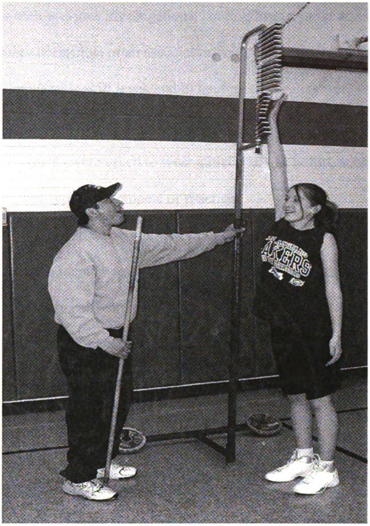

Figure 10. Assessment of participant maximum standing reach used in the determination of maximum vertical jump height.

Session 3: Pre-intervention Data Collection Session

In concert with previous investigations, landing from a jump was chosen as the experimental activity because a) of an association with ACL injury mechanisms, b) all subjects were of comparable skill level, and c) landing constraints were readily controllable in the experimental setting (Ford, Myer, & Hewett, 2003; James, Dufek, & Bates, 2000). Participants were asked to wear athletic shorts, t-shirt, socks and the footwear in which they typically compete or practice.

Twenty-four retro-reflective markers were placed on each subject at selected anatomical landmarks to identify and represent two dimensional position data of the lower and upper extremity body segments in space. The specific location of these markers were as follows: right and left distal ulnar head, right and left lateral humeral condyle, right and left acromioclavicular joint, right and left greater trochanter, right and left lateral femoral condyle, right and left medial femoral condyle, right and left lateral malleolus, right and left medial malleolus, right and left lateral aspect of the heel for both feet, right and left dorsal aspect of each foot in the region of the second cuneiform bone, right and left 5th metatarsal head, and right and left 1st metatarsal head (Figure 11).

To mitigate the potential for measurement errors, a double-sided adhesive tape was used to affix each retroreflective marker at the designated anatomical landmarks (over clothing and skin), and then each marker was further secured to the body with more adhesive tape to ensure as little displacement as possible with respect to the designated anatomical locations.

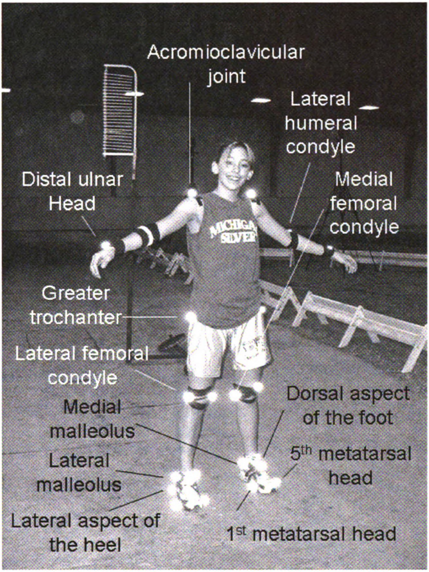

Figure 11. Retroreflective marker set-up for kinematic data collection.

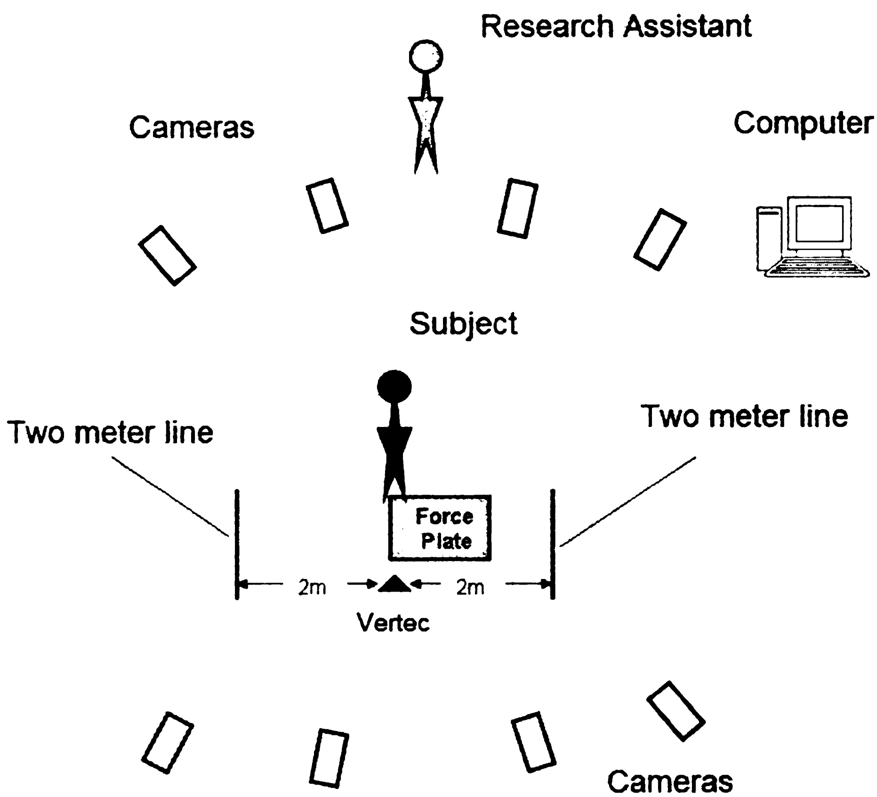

Figure 12. Schematic of laboratory instrumentation for biomechanical data collection.

Kinematic data were collected at 120 Hz with eight digital cameras (Falcon, Motion Analysis Corporation, Santa Rosa, CA) interfaced with a one gigabyte microprocessor computer (Dell Computer, Dallas, TX) and filtered with a low pass 4th order Butterworth filter at a cut-off value of 15 Hz as suggested by Van den Bogert and de Koning (1996). Three-dimensional calibration of the motion analysis system was conducted in accordance with those specifications recommended by the manufacturer, and one standing static trial was performed to achieve conformation and alignment of the two-dimensional joint coordinate system to the laboratory setting. Joint angular positions were derived from the kinematic data with zero degrees flexion defined as the knee joint position as the subject stood upright in a standing position. From the smoothed kinematic data, values associated with maximal right knee flexion angle on landing, and time to peak flexion parameters in the sagittal plane were derived.

Ground reaction forces (GRF's) under the right foot were collected at 1200 Hz using an AMTI LG6 force platform (Advanced Medical Technology Incorporated, Watertown, MA) with the gain set at 4000 Hz and time synchronized to the motion analysis system. All GRF data were smoothed with a low pass 4th order Butterworth filter at a cut-off value of 15 Hz as suggested by Van den Bogert and de Koning (1996).

Processing of all kinematic and kinetic raw data points commenced from one data point prior to the instant of right foot contact with the force plate, until that data point where maximal right knee flexion was derived from the landing associated with each jump task. An EvART Version 4.2 software program (Motion Analysis Corporation, Santa Rosa, CA) transformed retroreflective images of the markers into two-dimensional sagittal plane coordinates that were temporally synchronized and interpolated so that the number of data points matched those derived from the force plate.

Magnitude of the segmental masses for the leg and shank were derived from Jensen (1986), and the respective moments of inertia were estimated using equations from Winter (1990). Sagittal plane extensor moments of the right knee, defined by the local coordinate system of the subject, were calculated using an inverse dynamics method (Winter, 1990) that combined anthropometric, kinetic, kinematic, and GRF data exported into a source code developed with a MATLAB 7 software package (MathWorks, Nattick, MA, USA).

Inverse dynamics procedures were smoothed with a low pass 4^{th} order Butterworth filter at a cut-off value of 48 Hz (Van den Bogert & de Koning, 1996). Right knee extensor moments were assigned a positive direction and normalized by subject body mass as were the peak ground reaction forces on landing (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2004).

Pre-intervention Data Collection with Anticipated Conditions

To assess biomechanical parameters of the knee of each subject performing a jump task under anticipated conditions, each subject was asked to jump and tap the Vertec™ at their individual assessed maximal jump height, land, and immediately sprint to the right for two meters (Figure 13). To accommodate for the various individual strategies associated with a jumping task, an 18-inch by one-inch by one-eighth inch strip of balsa wood was attached with duct tape to an acrylic vane representative of each subject's maximal vertical jump height. An "X" was transcribed on the bottom distal end of the acrylic vane to serve as a modified "target vane" for the subject while they performed the jump task (Figure 14).

In an attempt to have the subjects land on the force platform with their right foot when they performed the jump trials, the Vertec™ was placed in a position behind the force plate so that the modified target vane was parallel to the left side force plate border and the transcribed "X" was at the midpoint between the left side corners of the force platform (Figure 15). Subjects were able to identify the proper start position for the jumps and the designated two meter sprint distance with the placement of three strips of yellow duct tape on the laboratory floor. The center strip was placed on the laboratory floor along the left outside edge of the force platform, while two other strips, equivalent in length, were placed in parallel and two meters to the left and right of the center strip (Figure 16).

After a brief warm-up and prior to performing the jumping task, subjects' were asked to stand upright while straddling the center strip of tape placed on the border of the laboratory floor and force plate (Figure 16). The strip of tape was utilized in order to have subjects initiate all jump efforts with the right leg (dominant for all subjects) on the force plate and the left foot on the laboratory floor. The location of the force plate was not disclosed to the subjects in order to inhibit any alteration of jump and landing strategies.

In preparation for the jump and landing task, subjects were asked to assume a natural ready jumping position with their heads oriented forward and arms at their side (Figure 13). Upon the subjects confirming they were ready to jump, the principal investigator reverse counted, "three – two – one - Go!" for each trial. On the "Go" cue, each subject was instructed to initiate the jump and then tap the transcribed "X" on the modified target vane set at each subjects' maximal vertical jump position on the Vertec™. Immediately upon landing, subjects were instructed to sprint to their right for two meters past the designated strips of tape placed on the laboratory floor. Once past the designated two meter strip of tape, subjects were told they could decelerate using as much distance as needed until they came to a halt. Data from five complete trials with a sprint to the right and five complete trials with a sprint to the left were collected for each participant. All trials (both left and right) were summed to acquire the mean score under anticipated conditions.

Figure

force pl

Figure 13. Subject assumes the "ready" position with the right foot in contact with the force platform prior to a jump trial.

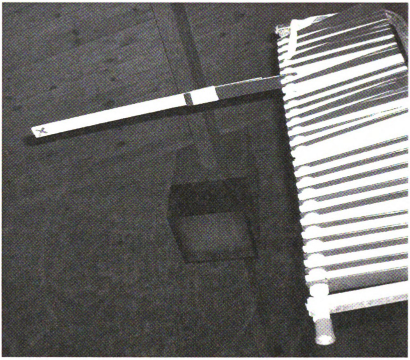

Figure 14. Transcribed "X" located on each subject's designated acrylic vane of the Vertec™.

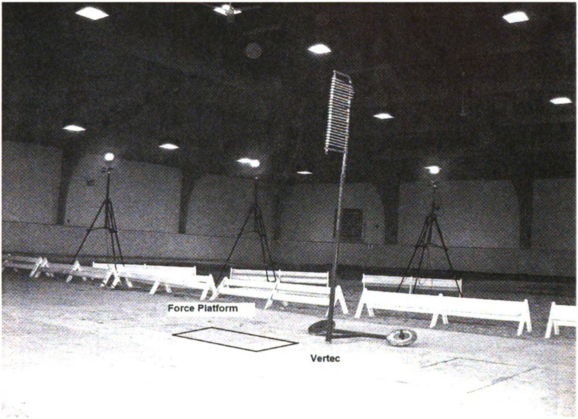

Figure 15. View of the testing area and position of the Vertec™ in proximity to the force platform.

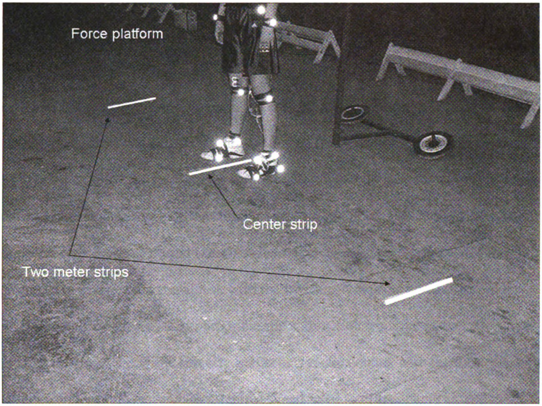

Figure 16. Landing area with the right foot placed on the force platform.

Pre-intervention Data Collection with Unanticipated Conditions

Specific placement of equipment and subjects for the unanticipated conditions were exactly the same as those test conditions utilized under anticipated conditions. To generate a scenario of an unanticipated landing situation, a research assistant was instructed to stand approximately four meters in front of the subject, with his back to the subject, upper extremities abducted to 90 degrees with the elbows flexed, and with his body out of the field of view of the motion analysis system (Figure 17). The research assistant was then administered a simple hand code from the investigator that indicated a right or left maximal effort two-meter sprint by the subject upon contact with the force platform or the laboratory floor for each maximal jump effort. To enhance the reliability of the hand code delivery during the trials, the research assistant was provided the opportunity to practice the signal task with the investigators prior to data collection.

Upon affirmation of the appropriate sprint direction from the investigator, and immediately upon hearing the subjects foot or feet make contact with the force platform or laboratory floor, the research assistant was instructed to immediately extend at the elbow joint and point with the index finger toward the designated sprint direction (Figure 18). No subject was provided any prior knowledge with respect to the direction of the sprint until a landing was initiated. Testing was conducted until five quality randomized trials in both the right and left direction were completed for each subject.

Figure 17. Research assistant in position to provide the directional cue for the subject with the unanticipated condition.

Figure 18. Research assistant providing the left directional cue for the unanticipated condition.

Dexterity Intervention

The dexterity training protocol (Appendix C) was administered to the experimental group twice per week over a six week time period and conducted on a regulation high school basketball court (approximately 26 meters in length by 15 meters in width) located in the Intramural Sports Circle Building on the campus of Michigan State University. To accommodate travel and time limitations on coaches, parents, guardians, and participants, each training session was conducted in addition to, and prior to practice or competition.

After a brief dynamic warm-up that included calisthenics, participants of the experimental group were randomly instructed to take designated positions along the baseline of the basketball court. The general scope of instruction for each session was to establish a continuum of motor activities initiated with the acquisition and performance of basic fundamental motor skill patterns that gradually evolved into a series of complex unanticipated motor tasks. In order to produce a "dextrous" environment while conducting the training program, the administration of the specific tasks to the participants was deliberately varied with respect to the complexity, speed, direction, distance, amplitude, and sequence (Appendix D). These training variables were manipulated through verbal instruction and the use of a whistle throughout the six week training period with the intent to create unanticipated movement scenarios that may be encountered under competitive basketball game conditions.

Upon comprehending the provided verbal instruction, each subject of the experimental group was instructed to respond to the whistle cues and perform the various dexterity tasks. Verbal feedback on performance of fundamental skills was provided for each task as deemed necessary by the investigator. Individual learning and performance variability among the participants with respect to the specific tasks was expected, however, no accommodations or alterations with respect to ability of the participants and the weekly training schedule were made by the investigators during the administration of the six week dexterity protocol.

Post Intervention Data Collection with Anticipated and Unanticipated Conditions

Upon completion of the six week dexterity training protocol, all participants were contacted and notified that they would have to be post tested under those conditions similar to those experienced under pre-intervention conditions. Subject preparation and specific placement of equipment for both the anticipated and unanticipated scenarios were exactly the same as data collection procedures prior to the intervention administered to the experimental group.

Data Analyses

Relevant baseline characteristics of the kinetic and kinematic parameters were calculated and evaluated through the use of descriptive statistics, specifically, means and standard deviations for the dependent variables under both anticipated and unanticipated jump landing conditions. Because random assignment of intact groups was utilized, an independent sample t-test was performed to determine if pre-existing group differences were evident at study entry for peak ground reaction force, peak knee joint flexion, time-to-peak knee joint flexion, and peak knee extension moment while landing from a jump with unanticipated conditions.

To explore if potential relationships among the various dependent variables existed, Pearson's correlations were performed with both the anticipated and unanticipated landing conditions for the post intervention time point. To test the study hypotheses related to potential group (control vs. experimental) differences over time (study entry vs. 6 weeks) for each of the dependent variables, a series of repeated-measures analysis of variance (ANOVAs), utilizing a mixed model analysis, were also conducted. Finally, a secondary aim of the study was to determine if significant pre-intervention differences existed between the anticipated and unanticipated landing conditions among all the involved participants. To test for these potential differences, paired sample t-tests were conducted for each dependent variable. All statistical analyses were conducted with SPSS Version 12.0 (SPSS Inc., Chicago, IL) utilizing a significance value of $p < 0.05$.

CHAPTER 4

RESULTS

Pre- and post intervention means and standard deviations for the dependent variables under anticipated and unanticipated conditions are presented in Tables 2 and 3. At study entry, pre-existing differences were found between the experimental and control groups for unanticipated time to peak knee flexion [$t(1,48) = -2.6$, $p<0.05$].

Pearson's correlations were conducted among the dependent variables and several significant moderate relationships were found. The relationship between unanticipated peak knee flexion angle and unanticipated time to peak knee flexion angle was strongest ($r = .72$, $p < .01$). Several other significant ($p < .05$) and expected correlations emerged among the dependent variables with anticipated landing conditions and are presented in Table 4.

To test the study hypotheses that a dexterity training protocol would be associated with a reduction in peak ground reaction force, peak knee flexion, time to peak knee flexion, and peak right knee extensor moment upon landing during unanticipated conditions, a series of repeated measures ANOVAs, utilizing a mixed model analysis, were conducted. For the dependent variable of peak ground reaction force, the Group (control, experimental) x Time (study entry, six weeks) interaction under unanticipated conditions was not significant [$F(1, 91) = .54$, $p = 0.47$]. However, for the main effects for Group [$F(1, 91) = 11.1$, $p<0.01$] and Time [$F(1, 91) = 10.3$, $p<0.01$], significant differences between the experimental and control groups were found. For the dependent variable of peak knee flexion on impact, the Group (control, experimental) x Time (study entry, six weeks) interaction under unanticipated conditions was not significant [$F(1, 97)$

= .007, $p = .93$]. Likewise, the main effect for Time was not significant [$F(1, 97) = .68$, $p = .41$]. However, the main effect for Group [$F(1, 97) = 14.6$, $p<0.01$] was significant, indicating noteworthy differences between the experimental and control groups. Similarly, for the dependent variable of time to peak knee flexion on impact, neither the Group (control, experimental) x Time (study entry, six weeks) interaction [$F(1, 106) = .49$, $p = .48$] nor the main effect for Time [$F(1, 106) = 2.9$, $p = .09$] were significant. However, a significant main effect for Group emerged [$F(1, 106) = 31.3$, $p<0.01$]. For the dependent variable of peak knee extensor moment on impact, there were no significant findings: [Group x Time: ($F(1, 104) = 1.96$, $p = 0.17$); Main effect for Time: ($F(1, 104) = .02$, $p = 0.88$); Main effect for Group: ($F(1, 104) = 3.3$, $p = 0.07$)].

Finally, results of paired sample t-tests exhibited significant differences for all variables of interest. Peak mean ground reaction force [t ($df = 24$) = -8.66, $p < 0.01$], mean peak angle of knee flexion [t ($df = 23$) = 5.53, $p < 0.01$], mean time to peak knee flexion on impact [t ($df = 27$) = 2.13, $p < 0.05$], and mean peak knee extensor moment [t ($df = 27$) = -2.93, $p < 0.01$] were all significantly different when comparing the anticipated to the unanticipated landing conditions.

Table 2

Results for the Dependent Variables Following a Maximal Vertical Jump Landing with Unanticipated Landing Conditions

Dependent Variable	*Results of the Investigation*
Peak Mean Ground Reaction Force	Group x Time interaction: Not significant Main effects for Group: Significant Main effects for Time: Significant
Peak Knee Joint Flexion	Group x Time interaction: Not significant Main effects for Group: Significant Main effects for Time: Not Significant
Time to Peak Knee Joint Flexion	Group x Time interaction: Not significant Main effects for Group: Significant Main effects for Time: Not Significant
Peak Knee Extensor Moment	Group x Time interaction: Not significant Main effects for Group: Not Significant Main effects for Time: Not Significant

Table 3

Means and Standard Deviations of the Dependent Variables with Anticipated Conditions

		Anticipated Condition					
		Experimental Group (n = 4)			Control Group (n = 2)		
		Total subject trials	mean	SD	Total subject trials	mean	SD
Ground Reaction Force[a]	pre-intervention	17	7.59	±3.16	10	7.07	±1.65
	post-intervention	23	12.89	±5.02	11	6.88	±1.28
Knee Joint Flexion (degrees)	pre-intervention	18	76.95	±11.9	10	67.4	±8.56
	post-intervention	23	73.6	±8.78	11	65.41	±4.93
Time to Peak Knee Joint Flexion (s)	pre-intervention	18	0.22	±0.06	10	0.16	±0.05
	post-intervention	23	0.2	±0.04	11	0.14	±0.07
Knee Extension Moment[b]	pre-intervention	18	3.75	±1.96	10	3.44	±1.44
	post-intervention	23	3.15	±1.48	11	4.13	±1.94

a = Ground reaction force values normalized by body mass.
b = Knee extensor moment values normalized by body mass.

Table 4

Means and Standard Deviations of the Dependent Variables with Unanticipated Conditions

		Unanticipated Condition					
		Experimental Group (n = 4)			Control Group (n = 2)		
		Total subject trials	mean	SD	Total subject trials	mean	SD
Ground Reaction Force[a]	pre-intervention	30	18.00	±4.26	20	15.96	±3.93
	post-intervention	38	19.80	±5.56	21	19.26	±3.47
Knee Joint Flexion (degrees)	pre-intervention	30	57.34	±7.38	20	55.65	±18.00
	post-intervention	39	63.98	±14.21	21	57.00	±7.6
Time to Peak Knee Joint Flexion (s)	pre-intervention	30	0.19	±0.03	20	0.16	±0.04
	post-intervention	39	0.21	±0.07	21	0.16	±0.03
Knee Extension Moment[b]	pre-intervention	30	4.54	±1.45	20	5.64	±2.89
	post-intervention	43	5.11	±1.69	21	5.38	±2.27

a = Ground reaction force values normalized by body mass.
b = Knee extensor moment values normalized by body mass.

Table 5

Pearson's Correlations for Dependent Variables for Anticipated and Unanticipated Conditions

	Anticipated Ground Reaction Force	Anticipated Knee Joint Flexion	Anticipated Time to Peak Knee Flexion	Anticipated Knee Extensor Moment	Unanticipated Ground Reaction Force	Unanticipated Knee Joint Flexion	Unanticipated Time to Peak Knee Flexion	Unanticipated Knee Extensor Moment
Anticipated Ground Reaction Force	1	.192	.185	.158	.380*	.621**	.556**	-0.218
Anticipated Knee Joint Flexion		1	.577**	-0.200	-0.306	.248	.374	-0.170
Anticipated Time to Peak Knee Flexion			1	-0.575**	-0.299	.218	.370*	-0.449**
Anticipated Knee Extensor Moment				1	.245	.005	-0.173	.373
Unanticipated Ground Reaction Force					1	-0.077	-0.299	.399**
Unanticipated Knee Joint Flexion						1	.723**	-0.427**
Unanticipated Time to Peak Knee Flexion							1	-0.368**
Unanticipated Knee Extensor Moment								1

* = Correlation is significant at the 0.05 level (two-tailed).
** = Correlation is significant at the 0.01 level (two-tailed).

CHAPTER 5

DISCUSSION

Variant landing and cutting movements are inherent characteristics in many popular sports and recreational activities. This study was unique in that it involved the acquisition and assessment of knee joint biomechanical parameters on adolescents performing a maximal vertical jump, landing, and then sprinting in an unanticipated direction. Because several of these biomechanical parameters have been suggested to possess a relationship with non-contact ACL injuries among female athletes, it is of practical value for allied health professionals, coaches, and athletes to gain greater understanding of how these specific biomechanical parameters can be altered to potentially attenuate the incidence of ACL injury among female athletes. Thus, the intent of this study was to investigate the effect of a dexterity training intervention on the following biomechanical parameters of the adolescent female knee joint during an unanticipated condition typical of that which may be experienced in a competitive or practice basketball setting.

Peak Ground Reaction Force

Quantifying the magnitude of the ground reaction force from a vertical jump can reveal insight with respect to understanding the influence of this variable on lower extremity landing mechanics. Principally, ground reaction forces contribute to the production of kinetic energy that is associated with impact and thus, is absorbed by the musculoskeletal structures (e.g., muscle, tendon, ligament, bone) while athletes land from a jump (Devita & Skelly, 1992). In addition, neuromuscular responses to impact on landing develop kinematic patterns within the lower extremities that provide an indicator as to the extent with which a "desirable" landing strategy may be employed to minimize the kinetic energy produced by those ground reaction forces on impact (Lephart et al., 2002; Malinzak et al., 2001).

Although studies employing an intervention to alter biomechanical variables with special landing characteristics are sparse, previous investigations have demonstrated the ability to decrease peak ground reaction forces after a prescribed and supervised physical training protocol. Hewett et al. (1996) implemented a six week plyometric and strength training program that decreased peak jump landing forces approximately 22% among a sample comprised of adolescent female volleyball athletes. In another study utilizing recreationally active female college students, Irmischer et al. (2004) employed a low-intensity plyometric exercise routine that reduced mean peak ground reaction force values of a jump task by approximately 26.4% over a nine-week training period. It should be recognized that the conditions for impact in both of the aforementioned investigations examined scenarios in which the subject was able to anticipate the conditions of landing.

The current study employed a six week dexterity intervention to determine if the protocol would significantly alter ground reaction forces on impact with an unanticipated landing condition. With respect to the Group x Time interaction, this investigation exhibited no significant decrease in mean peak ground reaction force, and interestingly, both the experimental group and the controls yielded increases (10% and 20.7%, respectively) in mean peak landing force upon completing the dexterity training program. Among both groups, only one participant (E2) demonstrated a decrease (10%) in mean peak ground reaction force over the six week training period. Mean peak ground reaction force values for each subject are displayed in Table 5.

One plausible explanation for the higher ground reaction forces may be attributed to the extremely variant nature of the landing task prior to an unanticipated directional sprint. Many sports, in general and basketball specifically, possess inherent multi-planar movement responses that are dictated by the special circumstances within the context of competition and/or practice. Unless these conditions are recognized immediately, there is little time to develop a voluntary or preferential motor response.

Although the focus of this investigation was not associated with examining landing strategies accompanying an anticipated condition, several participants employed a single-limb landing technique in preparation to place themselves in an advantageous position prior to push-off to enhance sprint performance. With unanticipated conditions it was clear that the nature of the aforementioned landing technique was effectively altered. All participants for all trials, pre- and post intervention, employed a double-limb landing stance on impact, perhaps to provide a stable base of support from which the subject could then react and then suitably align the lower extremities in the best possible position to perform the sprint task effectively.

It is apparent the ability to execute this strategy may have been conducted at the expense of reduced ground reaction forces and increased angles of knee flexion on impact. The findings of this study are in accordance with those of Sell et al. (2006) in that under reactive or unanticipated stop jump landing conditions, significantly enhanced ground reaction forces and decreased knee flexion was exhibited. Malinzak et al. (2001) and McClay et al. (1994) have stated that the combined effects of an enhanced ground reaction force and low measures of knee joint flexion on impact possess a relevant relationship with respect to lower extremity injury. In accordance, Lephart et al. (2002) and Malinzak et al. (2001) imply that the attenuation of ground reaction forces while landing from a jump or performing a cutting maneuver is dependent upon the necessary neuromuscular control to define those kinematic parameters (e.g., flexion, extension, adduction, abduction) that will provide the body with the most appropriate landing strategy on impact to prevent traumatic injury.

Table 6

Mean Peak Ground Reaction Force on Impact[a] for All Participants

Subject Identification	*Number of Trials*	*Pre-intervention*	*Number of Trials*	*Post intervention*
E1	9	20.1	7	24.3
E2	8	18.9	10	17.0
E3	4	18.2	3	26.7
E4	9	15.3	11	17.3
C1	10	13.5	9	17.0
C2	10	18.5	11	20.8

a = Ground reaction force values normalized by body mass.
Note. E = experimental group.
C = control group.

Peak Knee Flexion on Impact

The quadriceps exhibit lengthening in opposition to knee joint flexion during landing and this is reflected as a net joint extensor moment representing the muscle's role as a shock absorber. Extensible properties of muscle allow the tissue to absorb much of the impact associated with landing from a jump, and the degree of flexion on impact is an indicator that appropriate force attenuation is taking place (Sell et al., 2006; McClay et al., 1994; Devita & Skelly, 1992; Dufek & Bates, 1991). Limited ranges of motion of knee flexion on impact present a concern because this action may induce a greater "braking" contribution of the quadriceps thus producing excessive anterior tibial shear forces. Hence, the resultant loads placed on the ACL may be greater and manifest conditions conducive to producing traumatic injury (Chappel et al., 2002; An, 2002; Malinzak, et al., 2001; Hewett, 2000).

To date, there is no current literature regarding the influence of a physical training intervention on knee joint kinematics for subjects landing from a vertical jump with an unanticipated condition. Although not significant, group results for the current study demonstrated trends toward an increase in mean peak knee joint flexion on impact for both the experimental and controls over the six week training period. Participants within the experimental group enhanced knee joint flexion on impact with a mean value of 11.7% (6.6 degrees) while in comparison controls exhibited increased mean knee joint flexion of approximately 2.3% (1.35 degrees).

While the dexterity training protocol did not demonstrate significant alterations with the unanticipated landing condition, several investigations utilizing a training intervention have demonstrated the ability to alter this parameter with an anticipated landing condition. Although results were not significant, Hewett et al. (1996) enhanced the mean knee joint flexion on impact of his subjects approximately 3.0 degrees following a six week plyometric and strength training protocol. Following a comprehensive neuromuscular training program consisting of weight training, plyometrics, and balance training, Myer et al. (2005) demonstrated significant changes in knee flexion-extension range of motion for the right and left (4.0 and 5.0 degrees, respectively) knee joints as the subjects performed a drop jump followed by a subsequent vertical jump task.

Although the general group trend for the mean peak flexion values on impact for the current study appears to be encouraging, it must be recognized that the individual mean peak flexion data reflects abundant variation for both the experimental and control groups (Table 6). Similar to the mean peak ground reaction forces, it is probable that the extremely variant nature of the landing task prior to an unanticipated directional sprint dictates the neuromuscular response as a reflection of a scenario in which there is little time to develop a preferential motor response.

Because participants E2 (3.2 degrees), E3 (6.0 degrees), and C2 (16.8 degrees) exhibited trends toward enhanced knee joint flexion on impact, it was expected that each of the subjects would also demonstrate lower mean peak ground reaction forces thus reflecting greater force absorption on impact. Interestingly, only one participant (E2) exhibited a lower mean peak ground reaction force (- 10%) concomitant with increased knee joint flexion on impact. These results appear to imply that ground reaction force and angle of knee flexion on impact may not share the same relationship with the unanticipated landing condition as has been reported in previous investigations with the anticipated landing condition.

Although the trend for individual mean peak ground reaction forces were greater for the majority of participants in both groups, individual trends toward alteration of knee joint flexion on impact are mixed. Because there was a defined motor task (sprint) attached with the unanticipated landing condition, it is plausible that the landing strategy selected by the participants was closely aligned with performance outcome. DeVita and Skelly (1992) have stated that although stiff landing techniques afford the performer the opportunity to move faster or quickly after ground contact, this may occur at the expense of producing potentially greater joint moment and power values which concomitantly can be associated with a greater risk for injury.

Table 7

Mean Peak Knee Flexion on Landing for All Participants

Subject Identification	*Number of Trials*	*Pre-intervention (degrees)*	*Number of Trials*	*Post intervention (degrees)*
E1	9	54.8	12	47.9
E2	8	57.3	11	60.5
E3	4	74.4	9	80.4
E4	9	70.7	11	70.6
C1	10	72.3	9	58.0
C2	10	38.9	12	55.7

Note. E = experimental group.
C = control group.

Time to Peak Knee Flexion on Impact

Devita and Skelly (1992) have emphasized that in order for muscle to effectively contribute to the dissipation of kinetic energy on impact, it requires not only greater angular ranges of knee flexion, but more time from initial impact to peak knee flexion. Lephart et al. (2001) concur with this position by supporting the notion that peak flexion angle on impact and time to peak flexion angle become valuable indicators of the ability to attenuate ground reaction forces from a landing or cutting maneuver.

For this study, neither group exhibited significant post training changes, although the experimental group did demonstrate a trend toward enhanced mean time to peak knee flexion upon contact with the force platform. Mean time to peak knee flexion on impact increased from pre- to post intervention approximately 10.5%, while controls did not exhibit alterations of this parameter. However, because of significant pre-existing group differences and a small subject population at study entry, these results must be interpreted cautiously and strongly imply that alterations for the dependent variable time to peak knee flexion, may likely be due to chance.

Individual values for mean time to peak knee flexion are located in Table 7. For the experimental participants of the study, the trend for the increased time to peak knee flexion is in concert with an enhancement of peak knee flexion on landing. Pearson's correlations for peak knee flexion angle and time to peak knee flexion angle with the unanticipated landing condition demonstrated the strongest relationship ($r = .72$, $p < .01$) for these two dependent variables. Although subject E1 experienced a decrease in mean time to peak knee flexion concurrent with a decrease in mean peak knee flexion, subject E2 was the only participant to decrease mean peak ground reaction force upon landing while the others actually exhibited an increase in mean peak ground reaction force.

Similar to the findings within the experimental group, results among the control subjects were mixed with participant C2 experiencing enhanced mean peak knee flexion and time to peak knee flexion on impact with a concomitant increase in ground reaction force. For several subjects, the trends exhibited within the current study are in contrast to the expectation that mean peak ground reaction forces will decrease in concert with an increase of mean peak knee flexion and mean time to peak knee flexion. Because investigations determining time to peak knee flexion on impact of subjects performing unanticipated landing conditions are rare, it is difficult to ascertain mechanisms behind this trend among participants of both the experimental and control groups.

Generally, it has been demonstrated (Elkhart, et al., 2002; DeVita & Skelly, 1992; Bates & Dufek, 1991) that time to peak knee flexion and peak knee flexion on impact share a strong relationship with respect to landing while simultaneously reducing ground reaction forces. In light of these reports, all of which have been conducted under anticipated landing or cutting conditions, results of the current study appear to infer the premise that the reduction of ground reaction force and an increased time to peak angle of knee flexion on impact may not share the same relationship with the unanticipated landing condition as is encountered with the anticipated landing condition.

Table 8

Mean Time to Peak Knee Flexion on Impact for All Participants

Subject Identification	*Number of Trials*	*Pre-intervention (seconds)*	*Number of Trials*	*Post intervention (seconds)*
E1	9	0.16	12	0.14
E2	8	0.20	11	0.21
E3	4	0.22	9	0.27
E4	9	0.19	11	0.22
C1	10	0.19	9	0.18
C2	10	0.13	12	0.15

Note. E = experimental group.
C = control group.

Peak Knee Extensor Moment on Impact

Previous investigations have identified net knee joint extension moments acting eccentrically to control knee joint flexion and absorb the kinetic energy associated with landing or cutting tasks (Chappel et al., 2002; McClay, 1994). For the current study, peak knee extensor moments exhibited no significant change from pre- to post test for both the experimental group and controls. Examination of group trends revealed that the experimental group experienced an increase of normalized mean peak knee extensor moment of approximately 12.5% after the dexterity intervention, while over time, controls demonstrated a decrease in this parameter of approximately 4.8%.

Peak knee extensor moments have been associated with peak proximal anterior shear forces at the knee, often linked with minimal knee flexion on impact, increased quadriceps activity, decreased hamstring activity, or a combination of all three circumstances. It has been hypothesized that landing scenarios, where these conditions exist, may lead to uncharacteristically high and potentially injurious knee extension moments that are also associated with excessive ground reaction forces (Chappel et al., 2002; DeVita & Skelly, 1992).

Among experimental group participants, only subject E2 experienced a decrease in net right knee joint extensor moment over the six week training period. In addition, this participant also exhibited altered biomechanical parameters (decreased ground reaction force, increased knee joint flexion on impact, and increased time to peak knee flexion) conducive to a decrease in net knee joint moment on impact and consistent with previous investigations (McClay et al., 1994; Devita & Skelly, 1992; Dufek & Bates, 1991). This pattern was not typical of the other experimental group participants, the remainder of which demonstrated trends among the biomechanical parameters that were quite mixed (Table 8). Although control subject C2 did demonstrate enhanced mean peak knee flexion, time to peak knee flexion, and a decreased net right knee extensor moment on impact with the force platform over time, these results did not correspond with an attenuated ground reaction force and thus, do not correspond with the findings of McClay et al. (1994) and Chappel et al., (1992) in that smaller ground reaction forces typically result in smaller net knee extensor moments on impact with the ground.

Because this investigation is the only study to date that incorporates a vertical jump-landing task with a subsequent unanticipated sprint task, it is difficult to compare the results of this study to previous investigations that utilized anticipated landing conditions or cutting maneuvers (Sell et al., 2006; Myer et al., 2005; Irmischer et al., 2004; Hewett et al., 2002; Chappel et al., 2002; Malinzak et al., 2001; McClay, 1994; DeVita & Skelly, 1992). What is readily apparent with the unanticipated landing scenario is that the dependent variables representing the biomechanical parameters associated with landing from a vertical jump task appear to be in contrast with the expected trends associated with several of the aforementioned studies.

These findings suggest that changes in the landing characteristics (e.g., nature of the drill, height of the jump, posture, and center of gravity) during an unanticipated condition compare favorably with an altered landing task, thus the potential for increased external loads applied to the knee joint in comparison to the anticipated landing situation. Besier et al., (2001) have expressed that when potentially destabilizing forces threaten the integrity of the anatomical structures, the central nervous system is capable of adjusting muscle activation patterns to counter the large flexion loads to the knee muscles surrounding the joint and additionally, must apply a large extension moment that may result in a net anterior force to the tibia when the knee is near full extension. This mechanical predisposition is thought to be a prerequisite for serious ACL injury (Lephart et al., 2002b; Besier et al., 2001; Colby et al., 2000).

Table 9

Mean Peak Right Knee Extensor Moment[a] for All Participants

Subject Identification	*Number of Trials*	*Pre-intervention*	*Number of Trials*	*Post intervention*
E1	9	5.4	12	6.8
E2	8	4.0	10	3.6
E3	4	4.7	9	5.1
E4	9	4.0	11	4.6
C1	10	3.8	9	4.1
C2	10	7.5	12	6.5

a = Right knee extensor moment values normalized by body mass.
Note. E = experimental group.
C = control group.

There is compelling evidence that extrinsic factors (e.g., agonist-antagonist co-contraction, greater extension moment values on impact, less knee joint flexion on impact, and faster times to peak flexion) associated with ACL injury are significantly influenced by the neuromuscular control exhibited on muscles surrounding the knee joint (Irmischer et al., 2004; Cerulli et al., 2001; Wojtys et al., 2000; Hewett et al., 1999; Hewett et al., 1996; Huston & Wojtys, 1996). Because proprioceptive inputs define the regulation of neuromuscular control including muscle stiffness and kinesthesia, physical training protocols have been devised as a means of altering the biomechanical parameters associated with these extrinsic factors (Myer et al., 2005; Irmischer et al., 2004; Hewett et al., 2002).

In general, the literature emphasizes two key analytical criteria to assess the effectiveness of a physical training protocol with regard to minimizing ACL injury among female athletes. The first is associated with the ability to objectively assess the resultant altered biomechanical parameters that represent the output function of the dynamic joint stabilizing factors (e.g., joint moments, joint kinematics, and ground reaction forces) that dictate a suitable landing technique for the dissipation of the kinetic energy on impact while landing from a jump. Second, and very likely susceptible to many variables beyond the control of any investigation, does the physical training program actually demonstrate the ability to minimize the frequency and severity of knee injuries associated with sport?

This study examined the effect of a physical training program, encompassing fundamental motor tasks and elements of dexterity, on several biomechanical parameters (peak ground reaction forces, peak knee joint flexion, time to peak knee joint flexion, and peak knee extension moments) among adolescent female basketball athletes landing with an unanticipated condition (unknown direction of sprint). Although previous investigations have yielded results that provide strong evidence that physical training programs have the ability to alter neuromuscular (proprioceptive) response and decrease the incidence of serious ACL injury (Myer et al., 2005; Irmischer et al., 2004; Hewett et al., 2002; Hewett et al., 1996), this investigation did not provide significance for any of the proposed hypotheses. Despite a quality number of trials for each subject, the lack of significance may in fact be associated with a major limitation of this study in that the sample size was extremely limited, thus an understanding of the results for this study must be interpreted cautiously. Although the subject pool was small, it should be acknowledged that the adolescent female basketball athletes participating are considered to possess advanced skills and motor abilities for their chronological age grouping. What bearing this may have on the results of this study are unknown but must be considered in light of other sample populations in previous investigations that did not utilize athletes of comparable skill and motor ability (Myer et al., 2005; Irmischer et al., 2004; Hewett et al., 1996). Because AAU female adolescent basketball players are typically representative of athletes that exhibit excellent motor control and skill specifically for the sport of basketball, it was expected that this group would possibly exhibit minimal quantitative change among the biomechanical parameters collected. This was assumed because the proprioceptive mechanisms during jump landings are routinely challenged from the extensive exposure during high volume practice and competition for this elite population.

In spite of the lack of statistical significance, the dexterity training did generate desirable trends, chiefly increased mean peak flexion of the knee and mean time to peak knee flexion that may imply the establishment of alterations of the neuromuscular system upon impact with the ground. Of interest is the fact that an increase among these parameters will typically produce a concomitant decrease in peak ground reaction force and the knee joint extensor moments. Ironically, it was evident that the latter parameters generally exhibited an increase in value, both of which are typically associated with serious ACL injury.

Although suitable developments associated with the dexterity training protocol did exist for this study, the specific subject population and unanticipated jump landing conditions make it difficult to generalize these results to similar age-group or other female basketball populations. However, it should be considered that adolescent female athletes of lesser ability exposed to greater doses of dexterity and basketball training may exhibit modest to dramatic alterations among the biomechanical parameters simply due to the opportunity to refine proprioceptive mechanisms associated with a basketball specific task such as a jump landing. As a result, it would be of interest to initiate a future study that compared recreational female basketball athletes to those categorized as elite to examine if the magnitude of change among the biomechanical parameters is significant among these groups.

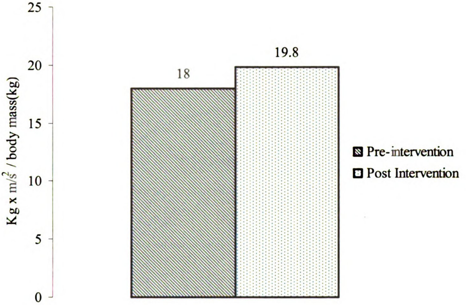

Figure 19. Mean normalized peak ground reaction force on impact for the experimental group.

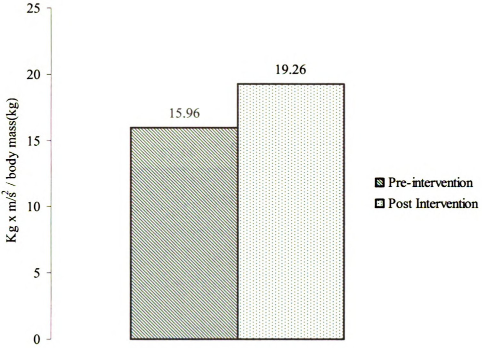

Figure 20. Mean normalized peak ground reaction force on impact for the control group.

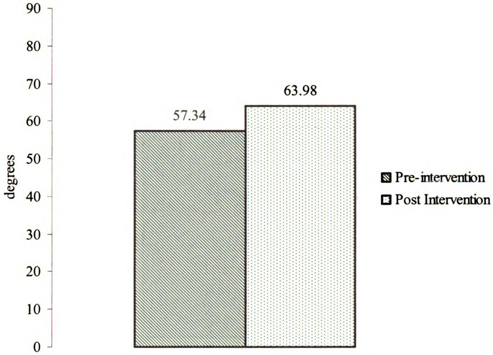

Figure 21. Mean peak flexion of the right knee on impact for the experimental group.

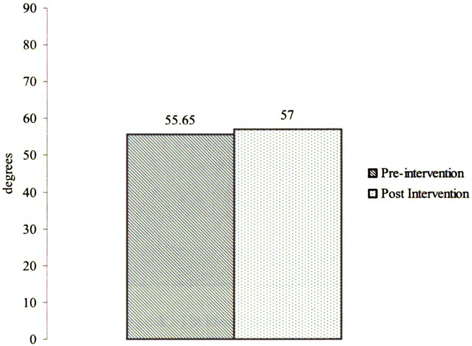

Figure 22. Mean peak flexion of the right knee on impact for the control group.

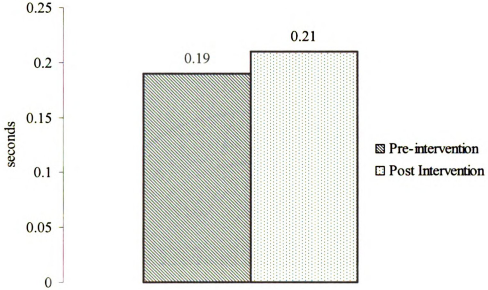

Figure 23. Mean time to peak right knee flexion on impact for the experimental group.

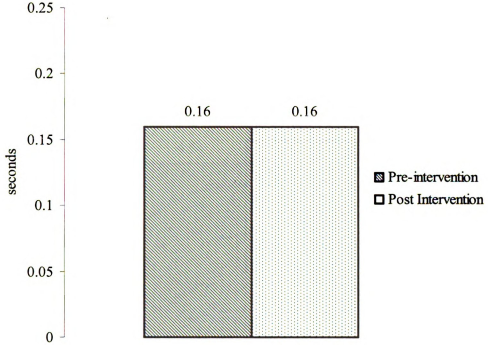

Figure 24. Mean time to peak right knee flexion on impact for the control group.

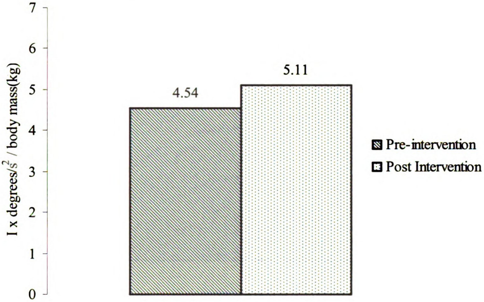

Figure 25. Mean peak normalized right knee extensor moment on impact for the experimental group.

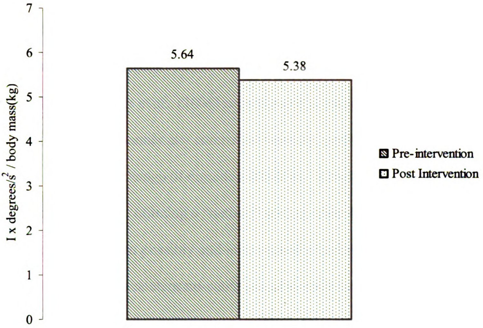

Figure 26. Mean peak normalized right knee extensor moment on impact for the control group.

Anticipated Versus Unanticipated Landing Conditions

It is important to consider that this study employed a landing scenario that is unique in comparison to other investigations discussed within the literature. Thus it is difficult to compare the results to aforementioned research projects to the current research which used an unanticipated impact condition. Studies by Besier et al., (2001), Neptune et al., (1999) and Myer et al., (2005) incorporated a setting in which the athlete, while sprinting in a linear manner at a controlled velocity, performed an unanticipated angle-of-cut upon receiving a change of direction stimulus. Cowling and Steele (2001) created an unanticipated scenario utilizing a "netball" setting whereby a jump task was conducted by the participant and then possibly and unexpectedly having a netball thrown in their direction to produce a catch or no-catch scenario upon landing.

Because Powell and Barber-Foss (2000) have reported the rebound task during basketball practice to be the most common event associated with knee injury among high school female basketball athletes in the United States, the landing task for this investigation was devised to assimilate this frequent and fundamental skill. Practice and competitive scenarios produce situations that require an athlete to conduct multiple athletic tasks in an extremely variant and often, limited amount of time. As basketball athletes are expected to jump and tip or grab the ball while rebounding, they will eventually make contact with the ground, possibly with one limb or both subsequently protecting the ball, passing, shooting, or dribbling.

In conjunction with a testing scenario that provided an unanticipated condition, the dexterity intervention program for this study was devised to replicate the "controlled high-risk movements" implied by Hewett (2002), Malinzak et al. (2001), and Besier et al.

(2001) to initiate balance perturbations and reproduce rapid, unpredictable changes of direction often evident during competition and practice in the game of basketball. It should be noted that within the literature, the aforementioned authors do not clearly delineate the term "high-risk". However, it is expressed that the intent of these activities is to facilitate the development of multi-joint neuromuscular engrams that combine joint stabilization, acceleration, deceleration, and kinesthesia through intermittent protocols that progress from low-intensity simple unidirectional movement patterns to complex multi-planar patterns.

To compare potential differences among the biomechanical parameters associated with landing with an anticipated versus an unanticipated condition, a paired samples t-test was conducted at pre-intervention inclusive of all participants, control and experimental. This was done with the intent to further the position held by Hewett (2002), Malinzak et al. (2001), and Besier et al. (2001) that physical training programs should include those special "high-risk" intervention exercises because these tasks potentially assimilate movements conducted by an athlete during basketball competition or practice.

Results of the paired samples t-test demonstrate that the biomechanical parameters (mean peak ground reaction force, mean peak angle of knee flexion, mean time to peak knee flexion, mean peak knee extension moment) evaluated in this study possess significant differences indicating the neuromuscular system will respond with a different landing strategy when faced with an anticipated versus unanticipated condition. For sport medicine personnel, coaches, and physical educators that intend to initiate injury intervention programs, the ideal that these "high-risk" or unanticipated movement tasks be included in formal physical training programs to mitigate the prevalence of ACL injury appears to be a sound notion because these unexpected movements appear to be closely aligned with what is actually happening during a rebound on the basketball court and perhaps other uncertain motor events during the course of a competition or practice.

DeVita and Skelly (1992) assert that stiff landing techniques afford the performer an opportunity to move quickly after ground contact to conduct an athletic task as quickly as possible. For this study, upon landing from a maximal jump effort, the subsequent unanticipated sprint task afforded investigators the opportunity to assess the extent of peak knee joint flexion and time to peak knee joint flexion on impact, two parameters associated with a "stiff" landing technique. Based upon the findings among the dependent variables in Tables 2 and 3 at pre-intervention, it is plausible the subjects exhibited decreased peak ranges of angular displacement about the knee and decreased times to peak knee flexion in response to the unanticipated sprint task which was conducted as quickly as possible upon impact. If indeed these are the circumstances with which the neuromuscular system responds, it is evident that when one lands within the context of an unpredictable circumstance, the neuromuscular plan crafted is one with a tendency to provide a solution for sport task success at the expense of protecting structures affiliated with the knee joint.

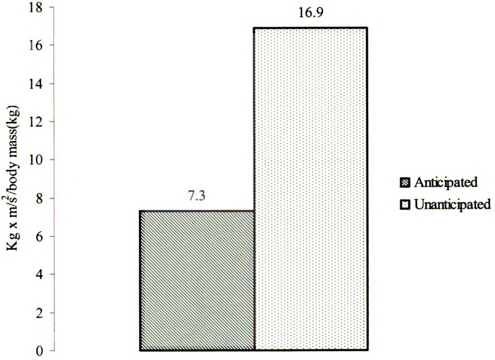

Figure 27. Mean normalized pre-intervention peak ground reaction force on impact: Anticipated versus unanticipated conditions for all participants.

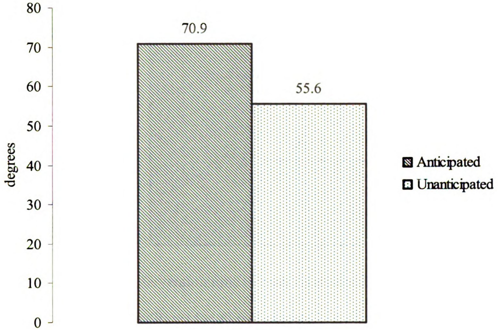

Figure 28. Mean pre-intervention peak flexion of the right knee on impact: Anticipated versus unanticipated conditions for all participants.

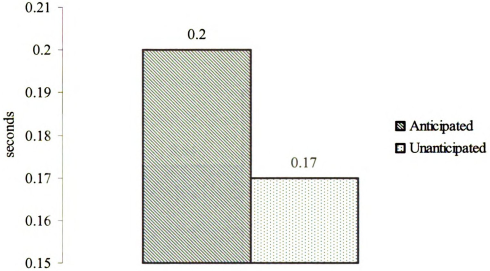

Figure 29. Mean pre-intervention time to peak right knee flexion on impact: Anticipated versus unanticipated conditions for all participants.

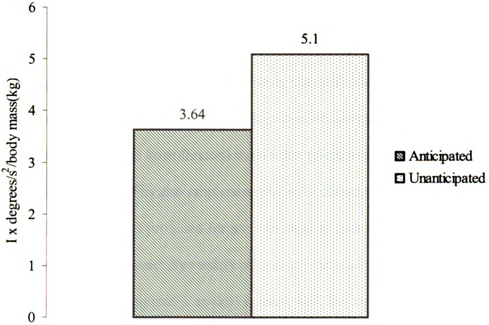

Figure 30. Mean pre-intervention peak normalized right knee extensor moment on impact: Anticipated versus unanticipated conditions for all participants.

Role of Unanticipated Training

Because unanticipated movements are readily apparent in the sport and recreational context, it could be proposed that the incorporation of "unexpectant" neuromuscular programming be included to potentially alter sensorimotor properties of muscle about the lower extremities in order to potentially mitigate the injurious neuro-mechanisms (e.g., latent quadriceps - hamstring firing) associated with ACL injury. Besier et al. (2001) furthers this ideal with the notion that "familiarizing" an athlete to unanticipated, rapid changes in direction rather than preplanned motions will direct the CNS to generate the proprioceptive sensitivity that will elicit appropriate neuromuscular adjustments (e.g., quadriceps and hamstring co-contraction, increased knee joint flexion on impact, time to peak knee flexion) within the movement. Rodacki et al. (2002) and Heiderscheit et al. (1998) also emphasize that neuromuscular response is enriched only when the opportunity is provided for an individual to repeatedly solve a challenging motor problem and potentially modify muscle properties that reflect a favorable solution to a motor task. Consequently, as skill is improved, the variability of motor task performance is decreased because the CNS will select a pattern that defines optimal motor efficiency.

Although neither paper introduced by Rodacki et al. (2002) and Heiderscheit et al. (1998) provide a specific timeline for proprioceptive changes to occur with practice, it would appear that sensorimotor adaptation, combining feedback and feed forward activity of the CNS, may introduce muscular responses that generate engrams capable of modifying the internal forces and protecting structures of the knee that are at the highest potential for injury (Hewett, 2002; Cerulli et al., 2001). These engrams are vital because ligaments become "unloaded" with enhanced muscular contributions from various co-contracting muscles and muscle groups and the resultant joint integrity is established through sufficient internal muscle force production to counter the external forces produced on impact while landing from a jump (Schultz et al., 2001).

Dexterity in the Context of ACL Injury Prevention for the Female Athlete

Bernstein (1996) has proposed dexterity as that ability of the nervous system to develop a quick and simple motor solution to a motor problem. To elaborate, to be dexterous does not propose that an individual perform balanced, synchronized, or coordinated movements, but rather generate an ability to forecast variant conditions in the external environment and further, to plan responsive movements accordingly.

Although the current investigation did not yield significant changes among the dependent variables, there were directional changes among the biomechanical parameters indicating that the nervous system may in fact be in the process of altering some capacity of neuromuscular control. In concert with these parameter patterns, for the dependent variables of peak ground reaction force, peak knee flexion, and time to peak knee flexion there were several significant statistical events associated with the main effects of Group and Time. For peak ground reaction force, both groups exhibited increases in unanticipated impact force from pre- to post intervention, however the magnitude of increase was greater among the controls (20.7%) in comparison to the experimental group (10%). Peak knee flexion increased among the controls 2.3% in comparison to an 11.7% increase for the experimental group demonstrating a significant difference for the main effect of Group. Time to peak knee flexion was also significant for the main effect of Group with the controls exhibiting no alteration in this dependent variable and the experimental group enhancing this measure approximately 10.5%.

Except for the direction of peak mean ground reaction force, the aforementioned findings may imply that although the current dexterity protocol did not significantly alter the biomechanical parameters, with respect to the trends that did occur between both groups, there indeed may be some support for the use of dexterity training to enable positive alterations of the dependent variables associated with non-contact ACL injury. It may be reasonable to imply that if the current intervention were applied over a longer period than six weeks, the possibility exists that the training program may have induced significant results congruent with the proposed hypotheses of this study.

What is clearly evident with respect to the diversity of the data collected is that there exist contrasts among the traits of the biomechanical parameters in comparison to previous investigations that have explored the anticipated landing condition exclusively. This is of special interest because it could be argued those ACL injury prevention programs that solely offer anticipated exercises or movements with the expectation of altering biomechanical parameters may actually impart shortcomings with regard to what actually occurs in the competitive and practice setting.

Investigations including the element of unpredictability within the scope of intervention to alter biomechanical parameters of the knee are scarce. To date, only one investigation has implemented the resemblance of an unanticipated programming element specifically utilizing activities with unanticipated cutting maneuvers (Myer et al., 2005). In concert with Bernstein's (1996) proposed definition of dexterity, it is apparent that intervention programs, including the protocol used in this study can be ambiguously created to resemble a category of "exercisability" that contain distinct features of unpredictability and require the trainee to produce variant solutions in response to a changing motor environment. Consequently, muscle dominant neuromuscular adjustments (e.g., hamstring and quadriceps co-contraction) are generated to provide varus/valgus and extensor support to the knee as it extends to stabilize while loading. Although joint contact forces are expected to increase, joint compression via co-contraction will enhance joint stability to acquire the limb positional control that, in conjunction with joint surface congruency, will act to potentially unload ligaments during mechanical loading on impact with the ground (Winthrow et al., 2006; Lloyd & Buchanon, 2001; Demont et al., 1999).

Physical Growth and Maturation

In conjunction with muscle control factors that exude influence on the extrinsic mechanisms that occupy a vital role with regard to non-contact ACL injury, it must be recognized that the typical process of physical growth and maturation among female basketball athletes demand greater attention than previously received (Davis & Ireland, 2003). An understanding of this area is special because initiation of physical maturation may induce subsequent anthropometric and skeletal changes (e.g., limb growth, changes in the distribution of body mass) that have the potential to alter various neuromechanical parameters of the lower extremities as they interact with the external environment.

This scenario introduces two questions that need further elaboration: 1) What is the appropriate age for the female athlete to be exposed to a physical training intervention to mitigate the potential for non-contact ACL injury? 2) Second, if the physical training intervention is applied prior to the initiation of dramatic anthropometric and skeletal changes (pre-pubescent), will the participant be able to preserve the enriched feed forward and feedback neuromechanisms associated with mitigating traumatic ACL injury throughout adolescence and into adulthood?

In addressing the first question, because the onset of physical maturation induces the expression of hormonal, anatomical, and behavioral change, the use of chronological age as a defining parameter from which to decide when to implement a physical training program to mitigate ACL injury is difficult because the timing and tempo of physical maturation is extremely variable (Malina, 1994; Malina & Bouchard, 1991). To address the second issue, it would be desirable to incorporate a longitudinal design that assessed biomechanical parameters prior to the initiation of puberty until adult physical maturity status has been achieved, and then determine if indeed these mechanical factors have been consistent or altered over time.

To date, no published investigation has implemented a method of assessing maturity status among adolescent female participants associated with an ACL injury intervention project. While examining lateral, static, and vertical landing sequences among pre-pubescent and post pubescent female athletes, Hass, Schick, Chow, Tillman, Brunt, and Cauraugh (2005) determined the peak knee extensor moment to be significantly greater among the pre-pubescent group during lateral and static landing conditions. According to the authors, these findings suggest there may be maturational considerations aside from the gender considerations that have been previously reported (Chappel et al., 2002; Malinzak et al., 2001; Huston & Wojtys, 1996). Unfortunately, this study did not utilize a maturity indicator to distinguish between biological and chronological age, thus blurring the distinction between pre-pubescent and post pubescent status.

Mandelbaum et al. (2005) conducted a two-year study to assess the influence of a neuromuscular and proprioceptive intervention training program on the incidence of ACL injury among adolescent female soccer athletes. Athletes varied in age from 14 to 18 years but unfortunately no maturity assessment was performed, although to date, this study possesses the greatest longitudinal component in comparison to previous intervention studies. In comparison to controls, the experimental group exhibited an 88% decrease in ACL injury for year one, and a 74% decrease in ACL tears for year two of the study demonstrating the effectiveness of the intervention for this chronological age group over the two year period.

The process of maturity assessment is often awkward, unreliable and invasive, particularly among adolescent subjects. Because the assessment of maturity status was previously non-existent within the ACL injury intervention research setting, this investigation implemented the non-invasive Khamis-Roche (1994) method to gain greater perspective on the maturational status of the elite adolescent female basketball athlete using a derived percentage of predicted adult height. The Khamis–Roche method (1994) assumes that individuals closer to their predicted adult height than would be expected for their age and gender possess advanced maturational status. To clarify, the mean percentage of adult height already achieved in girls at age of 13 years is 95.96% (Bayer & Bayley, 1959), thus a girl who has attained 97% of her predicted adult height would be considered advanced in her maturity status. For this investigation, results of the maturity indicator can be found in Table 1. Evaluation of the participants indicate subjects E1 and

E2 are extremely close to their expected predicted adult stature for age, subjects C2 and E3 exhibit late maturational status, and subjects C1 and E4 are advanced in maturational status with respect to predicted adult stature for age. Although these parameters are exclusively reported as descriptive characteristics, it should be noted that it is the "post" players, C1 and E4, that exhibit an earlier maturation status in comparison to the other participants and interestingly play a position typically requiring greater physical presence, tall stature and enhanced body mass.

The effect maturity status may have upon specific biomechanical parameters of the knee joint among adolescent female basketball athletes is currently unknown and warrants further investigation. Because the vast majority of intercollegiate female athletes are at or close to 100% of their adult height, they no longer undergo the same dynamic anthropometric and skeletal changes as experienced during puberty. Thus, the use of a specific maturity indicator or defined maturity status in opposition to the use of chronological age may provide a more reliable means through which an intervention can be introduced to help attenuate mechanisms associated with ACL injury. This approach may be more suitable for the adolescent female athlete because studies examining the mechanical characteristics of the intercollegiate female basketball athlete are difficult to use as a gauge to determine age appropriateness for the introduction of physical training interventions.

CHAPTER 6

SUMMARY AND RECOMMENDATIONS

Summary

Within the United States, ACL injuries among high school female basketball players annually occur at a rate of approximately 1 in 65 per participant (Hewett et al., 1999). Given these incidence figures, it is estimated approximately 7,000 ACL injuries will occur to female high school basketball athletes on an annual basis. Despite the fact that female athletes are typically initiating sports participation at an earlier chronological age, receive superior coaching education, and possess enhanced skills, the ACL injury rate has not declined significantly among intercollegiate female basketball athletes in the past decade (NCAA, 2004). Because the attenuation of ground reaction forces while landing from a jump may be associated with an athlete's neuromuscular capability to devise an appropriate landing strategy, efforts to understand the role of altered neuromuscular responses to training have been advocated to attenuate the potential for serious knee injury and in particular, ACL tears (Lephart et al., 2002; Malinzak et al. 2001).

The specific aim of this study was to examine the effects of a physical training program containing elements of dexterity on mean peak ground reaction forces, mean peak knee joint flexion, mean time to peak knee joint flexion, and mean peak knee extension moments among competitive adolescent female basketball athletes. Pre- and post intervention biomechanical data were collected from participants immediately upon landing from a maximal vertical jump effort and subsequently performing a sprint task in an unanticipated direction. The results of this study did not support the proposed hypotheses that the dexterity training program would produce significant changes among the dependent variables associated with an unanticipated landing condition. In contrast, previous investigations (Irmischer et al., 2004; Cerulli et al., 2001; Hewett et al., 1999; Hewett et al., 1996) utilizing a physical training intervention have demonstrated the ability to significantly alter various biomechanical parameters. However, these studies were conducted with training circumstances utilizing anticipated cutting or landing conditions.

Although the experimental group, employing the dexterity intervention, did not reveal significant changes among the dependent variables in this study, several biomechanical parameters did exhibit an unexpected albeit interesting trend with the unanticipated landing condition. The expectation that ground reaction forces would decrease in concert with a concomitant increase in peak knee flexion and time to peak knee flexion was not evident, inferring the reduction of ground reaction force, enhanced knee joint flexion and time to peak angle of knee flexion may not share the same association with the unanticipated landing condition as is demonstrated with the anticipated landing condition. Disassociation among these parameters was further supported with results garnered from a paired samples t-test. All of the dependent variables were significantly different when the anticipated and unanticipated landing characteristics were compared between both groups.

For several participants, the dexterity protocol did generate positive trends for knee flexion and time to peak knee flexion that may imply the initiation of alterations upon the neuromuscular system with exposure to the intervention. The uncharacteristic increase in ground reaction force may be reflective of a situation in which there was limited time to develop a preferred motor response. Thus, athletes faced with uncertain landing scenarios may call upon a variety of landing strategies to craft a solution for sport task success at the expense of protecting structures associated with the knee.

Previous interventions (Mandelbaum et al., 2005; Myer et al., 2005; Hewett et al., 2001; Wojtys et al., 1996; Hewett et al., 1996) have demonstrated success with a variety of training methods with which to intervene, thus adding to the difficulty of deciding which exercises are the best to prevent or mitigate ACL injury. However, based upon the results of this study, it could be implied those intervention programs that exclusively propose anticipated exercises or movements with the expectation of altering biomechanical parameters may actually impart shortcomings with regard to what actually occurs in the competitive and/or practice setting. Although not definitive, but worthy of further investigation, perhaps the rehearsal of "dexterous" activities in combination with successful anticipatory training methods may lead to the development of motor "engrams" that become more predictable and controllable over time. Thus, athletes may utilize their musculature to gain greater control of knee joint stability, enhance joint kinesthesia, and reduce the reliance upon ligamentous structures to preserve joint integrity while landing from a jump.

Finally, if combining dexterous exercises with other forms of intervention through physical training does alter biomechanical parameters associated with ACL injury, it may be important to identify an appropriate stage of physical development (e.g., childhood, adolescence, young adulthood) with which an injury intervention program could be implemented. Because there are expected anatomical changes associated with typical maturation that have the potential to alter established motor patterns, it would be interesting to determine if pre-pubescent athletes exposed to an injury intervention program would be able to enhance and maintain neuromuscular control throughout puberty and into young adulthood. Although investigations with the intent to determine if there are maturational considerations linked to ACL injury are sparse, further efforts with regard to understanding injury intervention should be encouraged to establish if consistent exposure to physical training can mitigate the frequency and severity of knee injuries associated with the female athlete.

Recommendations

Based upon the results of this investigation, there are several recommendations with regard to the establishment of future research directions concerning the ACL injury dilemma, the application of physical training interventions, and the adolescent female athlete.

- Future investigations should include a larger sample population with a sufficient number of participants in each group to determine the influence of the intervention on the dependent variables. Researchers should identify that an appropriate sample size is necessary to obtain a desirable effect size and power when using multivariate analysis techniques.

- Because it may be difficult to recruit an adequate number of elite-for-age female basketball athletes to participate in a given study, collaborations among institutions utilizing similar instrumentation and data collection procedures should work in unison with their respective sample sizes to ensure adequate statistical power is achieved.

- Future investigations that include female adolescent athletes should utilize a maturational assessment to gain greater insight into the timing of the physical growth associated changes that have the potential to alter neuromuscular parameters.
- Because growth and maturation of the adolescent female is extremely variable with regard to timing and tempo, the introduction of longitudinal investigations prior to the initiation of puberty until the mature state is achieved should be coordinated to determine what influence, if any, altered body segment and limb parameters have on neuromuscular control. Insight into this area may help establish a particular stage of growth that is the most appropriate to intervene in order to enhance the effectiveness of an ACL injury intervention program.
- Future research should explore variant applications involving dextrous exercises and drills, the frequency of their application, and the prescription of training to determine what potential impact this type of intervention may have on altering the neuromuscular system while landing or performing cutting maneuvers.
- To determine if there exist significant learning effects that account for the quantitative changes associated with the determination of neuromuscular control, future investigations should examine the implications of variant motor ability among adolescent female participants. Findings in this area may help elucidate whether significant differences are an indicator that poor motor ability or motor experience are a better indicator than gender with regard to the ACL injury dilemma.

- In addition to quantifying the knee extensor moments on landing, the assessment of muscular co-contraction among the quadriceps and hamstrings is an important neuromuscular factor that offers significant insight into the alteration of knee joint pathomechanics. Investigations utilizing electromyography (EMG) have established that females typically generate longer electromechanical response times, demonstrating the manifestation of muscular force at a slower rate when compared to males (Wilk, Arrigo, Andrews, & Clancy, 1999; Schultz & Perrin, 1999). Thus, the ability to assess muscle activity among the quadriceps and hamstrings may offer insight into the effectiveness of ACL intervention protocols and their ability to minimize quadriceps-hamstring firing latency while landing with the unanticipated condition.

It was the intent of this research paradigm to develop an ACL injury intervention protocol for the female adolescent athlete, easy to follow and modifiable, for application among various recreational, sport, and physical education settings. Potentially, the information from this study in concert with future investigations may help provide sport scientists, coaches, and athletes gain greater insight in an attempt to manage the intrinsic and extrinsic factors associated with non-contact ACL injury and consequently, produce less physical and emotional strain on the competitive adolescent female athlete.

APPENDICES

APPENDIX A

IRB Approval

MICHIGAN STATE
UNIVERSITY

February 3, 2004

TO: Eugene W. BROWN
204 IM Sports Circle Bldg

RE: **IRB# 03-880** CATEGORY: FULL REVIEW

APPROVAL DATE: February 2, 2004

EXPIRATION DATEJanuary 2, 2005

TITLE: THE INFLUENCE OF A DEXTERITY TRAINING PROGRAM ON BIOMECHANICAL PARAMETERS OF THE KNEE JOINT AMONG ADOLESCENT FEMALE BASKETBALL ATHLETES

The University Committee on Research Involving Human Subjects' (UCRIHS) review of this project is complete and I am pleased to advise that the rights and welfare of the human subjects appear to be adequately protected and methods to obtain informed consent are appropriate. Therefore, the **UCRIHS approved this project.**

RENEWALS: UCRIHS approval is valid until the expiration date listed above. Projects continuing beyond this date must be renewed with the renewal form. A maximum of four such expedited renewals are possible. Investigators wishing to continue a project beyond that time need to submit a 5-year application for a complete review.
REVISIONS: UCRIHS must review any changes in procedures involving human subjects, prior to initiation of the change. If this is done at the time of renewal, please include a revision form with the renewal. To revise an approved protocol at any other time during the year, send your written request with an attached revision cover sheet to the UCRIHS Chair, requesting revised approval and referencing the project's IRB# and title. Include in your request a description of the change and any revised instruments, consent forms or advertisements that are applicable.
PROBLEMS/CHANGES: Should either of the following arise during the course of the work, notify UCRIHS promptly: 1) problems (unexpected side effects, complaints, etc.) involving human subjects or 2) changes in the research environment or new information indicating greater risk to the human subjects than existed when the protocol was previously reviewed and approved.

If we can be of further assistance, please contact us at (517) 355-2180 or via email: UCRIHS@msu.edu. Please note that all UCRIHS forms are located on the web: http://www.humanresearch.msu.edu

Sincerely,

Peter Vasilenko, Ph.D.
UCRIHS Chair

PV: jm

cc: Anthony Moreno
1017 Delridge Rd.
East Lansing, MI 48823

Participant Consent Form

"The influence of a dexterity training protocol on biomechanical parameters of the knee joint among adolescent female basketball athletes."

Primary Investigator: **Eugene Brown PhD**, Department of Kinesiology,
Michigan State University
Secondary Investigator: **Anthony Moreno MS**, Department of Kinesiology
Michigan State University

This study is being conducted as a doctoral dissertation:

The purpose of this study is to determine the influence of a dexterity training program on motion characteristics of the knee joint among competitive adolescent female basketball athletes. These motion characteristics will be measured while performing a maximal vertical jump effort, landing and then immediately followed by a side-shuffling movement under both expected and unexpected conditions.

This study will attempt to identify changes, from prior to the training program to after the training program, among several mechanical characteristics of the knee. If you are a member of the experimental group, you will be prescribed a dexterity program that is composed of simple fundamental and basic movement tasks (e.g., jumping, skipping, shuffling, etc.) similar to those movements you encounter in a basketball game or at practice. Each session of the 6 week / two meetings per week dexterity program will take approximately 15 to 20 minutes to complete. Those that are members of the control group will follow their typical basketball practice and competition schedule for six weeks.

The study will help to identify those mechanical factors that may reduce the risk of knee injury and specifically, anterior cruciate ligament (ACL) damage among female basketball athletes. The anthropometric (height, weight, limb length) data collection session is estimated to last about 1.0 hour and each pre-test and post test kinematic and kinetic data collection session will last approximately 1.5 hours. You will be asked to participate in three data collection sessions to be scheduled on separate dates (Total data collection time for three sessions approximately 3.5 hours). It is important that the participants in the study be free of any previous orthopedic condition of the lower limbs (e.g., thigh, shank, foot) that may hinder their ability to perform a maximal vertical jump and shuffle maneuver. In addition, the participants should be free of allergies and conditions associated with equine animals. The data collection process will have the following stages:

1) **General Information** – After explanation and description of the study and subject consent, a questionnaire will be distributed among the participants to collect information with regard to self-perceived movement confidence in a basketball game setting. This questionnaire will be administered prior the collection of any anthropometric data.

2) **Anthropometric Measurements** – All anthropometric data will be collected in private (parents or guardians may accompany you) in the Department of Kinesiology's Biomechanics Research Station located in the IM Sports Circle Building on the campus of Michigan State University.

- Weight will be assessed on a standard weight balance while you are wearing shorts and t-shirt.
- Height will be assessed with a standard anthropometer.
- Sitting height will be assessed with a standard anthropometer while you are seated on a bench.
- Limb lengths will be determined with the use of standard body calipers. Specifically thigh, lower leg, and foot lengths will be measured.
- Parents will be asked to provide data with respect to self-reported height as part of a non-invasive maturity assessment.

3) **Determining Maximal Vertical Jump** – Your maximal vertical jump will be measured with a training device called a Vertec. You will be provided plenty of opportunity to learn and practice before the collection of the movement data.
4) **Kinematic/Kinetic Data Collection** - Kinematic data collection will involve the use of several digital video cameras to document the movement patterns of your body and body parts in the performance of the maximal vertical jump and landing task. The following order of activities will be followed:

- Before actual data collection, you will have 20 reflective joint markers attached to points on the segments of the lower limbs. In addition, you will have a very small portion of your thigh lightly abraded and cleansed in order to attach several surface electromyography (SEMG) electrodes necessary to measure thigh muscle activity.
- You will be asked to warm up as if you were about to participate in one of your standard basketball practice sessions.
- Following your overall warm up, you will be asked to perform vertical jumps, landings (total of 5 quality trials for both planned and unplanned landing conditions), shuffles and sprints. Note that there is no correct or incorrect performance. We only want to record your style of performance. You will be asked to assume a "ready position" prior to jumping at the target phalange on a Vertec device that will be adjusted to your determined maximal vertical jump height.
- Video cameras will be used to determine changes within the movement data and for comparing "before" dexterity training to "after" dexterity training results.
- In addition to the video recording of each jump trial, forces applied to the ground will be collected to assist in determining the forces that exist at the knee joint while jumping, landing and shuffling.

You are being asked to participate in this study because you are a competitive athlete in a selective youth basketball league. There is no monetary benefit from your participation. Your participation is totally voluntary, and you may chose to participate or not, as well as to discontinue your participation at any time without any explanation. By participating in this study you agree that the materials and data generated (video, pictures, and measurements) may be used for research and academic purposes and may be observed by participants within scholastic and/or research settings (e.g., classrooms, research presentations, seminars, etc). You have also been assured that your privacy will be protected to the maximum extent allowable by law. When this research project is completed, an abstract of the results will be mailed to you. You may also seek personal data for comparison of pre- and post test data.

In the unlikely event that you are injured as a result of your participation in this research project, Michigan State University will provide emergency medical care if necessary. If the injury is not caused by the negligence of MSU, you are personally responsible for the expenses of this emergency care and any other medical expenses incurred as a result of this injury.

Your signature(s) below, indicates that you give permission to the investigators to utilize/show videotapes and still images of your participation for academic purposes including research presentations, seminars and other clinical or classroom settings. Should you decide to withdraw from the study, all videotaped sessions and/or still images of your participation will be deleted and/or destroyed.

Signature of Participant: ______________________________ Date:__________

Signature of Parent / Guardian: ___________________________ Date:__________

If you have any questions about this study, please contact **Dr. Eugene Brown** ☎no. 353-6491, email: ewbrown@msu.edu, or **Anthony Moreno** ☎no. 351-9734, email: morenoan@msu.edu at the Department of Kinesiology, Michigan State University. If you have questions or concerns regarding your rights as a study participant, or are dissatisfied at any time with any aspect of this study, you may contact – anonymously, if you wish- **Peter Vasilenko, Ph.D.**, Chair of the University Committee on Research Involving Human Subjects (UCRHIS) by phone (517) 355-2180, fax: (517) 432-4503, email: ucrihs@msu.edu, or regular mail: 202 Olds Hall, East Lansing, MI 48824.

Name of participant:__________________________________
Date of birth:___________

Signature of participant:_____________________________________
Date:__________

Parental Consent Form

"The influence of a dexterity training protocol on biomechanical parameters of the knee joint among adolescent female basketball athletes."

Primary Investigator: Eugene Brown PhD, Department of Kinesiology,
Michigan State University
Secondary Investigator: Anthony Moreno MS, Department of Kinesiology
Michigan State University

This study is being conducted as a doctoral dissertation:

The purpose of this study is to determine the influence of a dexterity training protocol on biomechanical parameters of the knee joint among selective adolescent female basketball athletes. These biomechanical measures will be assessed while performing a maximal vertical jump effort and subsequently executing a side-shuffling movement under both anticipated and unanticipated conditions.

This study will attempt to identify potential pre-intervention and post intervention differences of the assessed biomechanical measures among adolescent female basketball athletes. If you are a member of the experimental group, you will be prescribed a dexterity protocol that is comprised of simple fundamental and basic motor tasks (e.g., jumping, skipping, shuffling. etc.) similar in scope to those tasks encountered in a basketball game or practice settings. Each session of the 6 week/ two meetings per week dexterity protocol will take approximately 15 to 20 minutes to complete. Those that comprise the control group will follow their typical basketball practice and competition schedule for six weeks.

The study will help to identify biomechanical alterations or adaptations that may mitigate the incidence of knee injury and specifically, anterior cruciate ligament (ACL) distress. The anthropometric data collection session is estimated to last approximately 1.0 hours and each pre-test and post test kinematic and kinetic data collection session will last approximately 1.5 hours. Subjects will be asked to participate in three data collection sessions to be scheduled on separate dates (Total data collection time for the combined three sessions approximately 3.5 hours). In addition, it is imperative that participants be free of any orthopedic condition of the lower extremities that may hinder their ability to perform a maximal vertical jump and shuffle maneuver, and be free of allergies and conditions associated with equine animals. The data collection process will have the following stages:

5) **General Information** – After explanation and description of the study and subject consent, a questionnaire will be distributed among the participants to collect information with regard to self-perceived movement confidence in a basketball game setting. This assessment instrument will be administered prior the collection of any anthropometric data.

6) **Anthropometric Measurements** – All anthropometric data will be collected in private (parents or guardians may accompany their child) in the Department of Kinesiology's Biomechanics Research Station located in the IM Sports Circle Building on the campus of Michigan State University.

- Weight will be assessed on a standard weight balance while you are wearing shorts and t-shirt.
- Height will be assessed with a standard anthropometer.
- Sitting height will be assessed with a standard anthropometer while you are seated on a bench.
- Segmental lengths will be determined with the use of standard body calipers. Specifically thigh, shank, and foot lengths will be assessed.
- Parents will be asked to provide data with respect to self-reported height as part of a non-invasive maturity assessment.

7) **Maximal Vertical Jump Determination** – Your maximal vertical jump will be assessed with a training assessment device called a Vertec. You will be provided ample opportunity to learn and practice prior to the collection of the kinematic and kinetic data.
8) **Kinematic/Kinetic Data Collection** - Kinematic data collection will involve the use of several digital video cameras to document the movement patterns of your body and body parts in the performance of the maximal vertical jump and landing task. The following protocol will be used:

- Prior to actual data collection, you will have 20 reflective joint markers affixed to points on the segments of the lower limbs. In addition, you will have a very small portion of your thigh lightly abraded and cleansed in order to affix several surface electromyography (SEMG) electrodes necessary to assess thigh muscle activity.
- You will be asked to warm up as if you were about to participate in one of your standard basketball practice sessions.
- Following your overall warm up, you will be asked to perform vertical jumps, landings (total of 5 quality trials for both planned and unplanned landing conditions), shuffles and sprints. Note that there is no correct or incorrect performance. We only want to record your style of performance. You will be asked to assume a "ready position" prior to jumping at the target phalange on a vertec device that will be adjusted to your assessed maximal vertical jump value.
- Video cameras will be used to determine quantitative and qualitative data with respect to comparing pre-intervention to post intervention results.
- In addition to the video recording of each jump trial, forces applied to the ground will be simultaneously collected to assist in the determination of forces that are incurred at the knee joint.

You are being asked to participate in this study because you are a competitive athlete in a selective youth basketball league. There is no economical benefit from your participation. Your participation is totally voluntary, and you may chose to participate or not, as well as to discontinue your participation at any time without any explanation. By participating in this study you agree that the materials and data generated (video, pictures, and measurements) may be used for research and academic purposes and may be observed by participants within academic and/or research settings (e.g., classrooms, research presentations, seminars, etc). You have also been assured that your privacy will be protected to the maximum extent allowable by law. When this research is completed, an abstract of the results will be mailed to you. You may also seek personal data for comparison of pre- and post test data.

In the unlikely event that you are injured as a result of your participation in this research project, Michigan State University will provide emergency medical care if necessary. If the injury is not caused by the negligence of MSU, you are personally responsible for the expenses of this emergency care and any other medical expenses incurred as a result of this injury.

If you have any questions about this study, please contact Dr. Eugene Brown ☎no. 353-6491, email: ewbrown@msu.edu, or Tony Moreno ☎no. 351-9734, email: morenoan@msu.edu at the Department of Kinesiology, Michigan State University. If you have questions or concerns regarding your rights as a study participant, or are dissatisfied at any time with any aspect of this study, you may contact – anonymously, if you wish- Peter Vasilenko, Ph.D., Chair of the University Committee on Research Involving Human Subjects (UCRHIS) by phone (517) 355-2180, fax: (517) 432-4503, email: ucrihs@msu.edu, or regular mail: 202 Olds Hall, East Lansing, MI 48824.

Name of participant:____________________________ Date:__________
Date of birth:____________

Name of parent (guardian):________________________
Signature of parent:______________________

Mailingaddress:____
Phone:__________________ e-mail address:____________________________

APPENDIX B

Physical Maturity Assessment

Khamis-Roche Method of Physical Maturity Assessment

To non-invasively assess the physical maturity status of all participants, height (HT) and weight (WT) measures were acquired during the anthropometric data collection session. This information was collected in conjunction with self-reported parental heights. To adjust for individual tendency to overestimate height, the following equations were implemented as provided by Epstein et al. (1995):

Adjusted Adult Height (females) = 2.803 + (0.953 x reported HT in inches)

Adjusted Adult Height (males) = 2.316 + (0.987 x reported HT in inches)

Predicted adult height of the adolescent female basketball athletes was determined using current age, height, weight, mid-parent height and a regression equation as proposed by Khamis and Rhoche (1994):

Predicted Height $= \beta_0 + \beta_1$ *(HT)* $+ \beta_2$ *(HT)* $+ \beta_3$ *(midparent height)* where;

β_0 is the intercept and β_1, β_2, and β_3 are the age and sex specific coefficients as provided by Bayer and Bayley (1959).

Percentage of predicted adult height was used to estimate maturity status using the following equation:

Percentage of Predicted Adult Stature = Present Stature / Predicted Adult Height

Chronological age and gender specific reference values for expected percentage of predicted adult height were acquired from data collected by Bayer and Bayley (1959).

APPENDIX C

Dexterity Protocol Skills

Skipping. While standing upright and maintaining good posture, initiate skipping by stepping forward, pushing off the ball of the forward foot, hopping off of that foot and then repeating these tasks for the opposite foot. Repeat in a pattern that assumes an alternating step – hop pattern off of each foot. Each foot will bounce off the ground twice before the other foot strikes the ground, as the arms move in opposition.

Back Skip. Back skipping is conducted in a similar pattern as observed when forward skipping. The exception is that the task is initiated while stepping backwards. Repeat in a pattern that assumes an alternating step – hop pattern off of each foot. Each foot will bounce off the ground twice before the other foot strikes the ground, while the maintaining the arms in a neutral position.

Crossover Sideskip. Moving in a lateral manner, cross the trail leg over the lead leg and skip. The original lead leg then steps behind the trail leg back into the lead position (only the trail leg crosses over). Each foot will bounce off the ground twice before the other foot strikes the ground. Try to get your shoulders to move with your hips as much as possible, without losing balance.

Side Shuffle. Side shuffling is a quick lateral stepping body movement. Start with a natural athletic stance with the head up and focused forward. The hands are at waist height and out in front of the body. Moving in the desired direction, push off the balls of the feet while keeping the feet at an equal distance between each shuffle so the feet do not come together.

Carioca. While keeping the head up and focused forward, assume a ready athletic position with the hips and both legs slightly bent. While moving in a lateral manner, the trail foot crosses in front of the lead foot. The lead foot then moves ahead of the trail foot. The trail foot then crosses behind the lead foot and continues this pattern for the recommended distance. Move and push off the balls of the feet while rotating the hips while keeping the arms from swinging too far from the body.

Front Carioca. While keeping the head up and focused forward, assume an upright position with the hips and both legs extended. While moving in a forward manner, the trail foot crosses in front of the lead foot as the lead foot subsequently moves behind the trail foot. This pattern repeats for the assigned distance. Move and push off the balls of the feet while directing the hips forward and keeping the arms from swinging too far from the body.

Hops in Place. Pushing off with one foot, "hop" in place for the required number of repetitions while trying to minimize displacement of the body in the horizontal or lateral sense while landing on the push-off foot. If executed properly, you should hop as high vertically as possible. As soon as you hit the ground, drive the arms upward to help acquire height and power. It is important to be as quick as possible off the ground. Repeat for the drill for the opposite leg.

Jumps in Place. Pushing off the balls of the feet, "jump" in place for the required number of repetitions while trying to minimize displacement of the body in the horizontal and lateral sense while landing with both feet. If executed properly, you should jump vertically as high as possible. As soon as you hit the ground, drive the arms upward to help acquire height and power. It is important to be as quick as possible off the ground.

Single Leg Line Hops. Start on the left side of a line on the court. Pushing off of the left foot, jump across the line, but also move forward. If executed properly, you should move across the line and forward quickly as you land consecutively on the push-off foot. It is important to be as quick as possible off the ground. For the right leg, initiate the drill on the right foot. This drill can also be performed in the backward sense.

Double Leg Line Jumps. Start on the left side of a line on the court. Pushing off with both feet, jump across the line, but also move forward. If executed properly, you should move across the line with both feet quickly. As soon as you hit, drive across the line and forward. It is important to be as quick as possible off the ground. This drill can also be performed in the backward sense.

Side Shuffle Drill. This drill requires the use of the primary investigator to give commands to the athlete with the use of a "single" or "double" whistle. This drill starts with the athlete in a start position and on the baseline of the basketball court. When the start command is given, the athlete will start by shuffling to the midcourt. When the "single" whistle is sounded, the athlete will shuffle in the opposite direction back to the starting point. If the "double" whistle is given, the athlete will perform a 180 degree turn and move in the same direction toward the midcourt. The single and double whistle commands will be interspersed while the athlete performs the side shuffling task.

Carioca Drill. This drill requires the use of the primary investigator to give commands to the athlete with the use of a "single" or "double" whistle. This drill starts with the athlete in a start position and on the baseline. When the start command is given, the athlete will start by carioca to the midcourt. When the "single" whistle is sounded, the athlete will shuffle in the opposite direction back to the starting point. If the "double" whistle is given, the athlete will perform a 180 degree turn and move in the same direction toward the midcourt. The single and double whistle commands will be interspersed while the athlete performs the side shuffling task.

APPENDIX D

Dexterity Training Program

Table 10

Dexterity Protocol: Week #1

Dynamic warm-up and stretch
• Double leg jumps in place; land "quiet" (5 sets of 5 contacts) • Skip (2x 29 meters) • Back skip (2x 29 meters) • Crossover sideskip (2x 29 meters) • Shuffling slow left (2x 29 meters) • Shuffling slow right (2x 29 meters) • Carioca slow w/ moderate gait amplitude (2 x 29 meters) • Carioca slow w/ large gait amplitude (2x 29 meters) • Carioca slow w/ small gait amplitude (2x 29 meters)
Practice/competiton.........cool down and stretch

Table 11

Dexterity Protocol: Week #2

Dynamic warm-up and stretch
• Double leg jumps in place; land "quiet" (3 x 5) • Double leg jumps forward slow (2x 14.5 meters) • Double leg jumps backward slow (2x 14.5 meters) • Double leg jumps side to side and forward at easy pace (2x 14.5 meters) • Double leg jumps side to side and backward at easy pace (2x 14.5 meters) • Skip forward to backward to forward.........easy pace....... (29 meters on the whistle) • Skip forward, sideskip, skip forward, sideskip.......easy pace...(29 meters on the whistle) • Backskip, crossover sideskip, backskip, crossover sideskip......easy pace...(29 meters on the whistle) • Alternate backskip/skip on single whistle...crossover sideskip on double whistle....easy pace... (29 meters) • Shuffling moderate pace left (2x 29 meters) • Shuffling moderate pace right (2x 29 meters) • Carioca moderate w/ moderate gait amplitude (2x 29 meters) • Carioca moderate w/ large gait amplitude (2x 29 meters) • Carioca moderate w/ small gait amplitude (2x 29 meters)
Practice/competition.........cool down and stretch

Table 12

Dexterity Protocol: Week #3

Dynamic warm-up and stretch
• Skipping forward (2x 29 meters) • Backskip (2x 29 meters) • Crossover sideskip (2x 29 meters) • Double leg jumps forward (2x 14.5 meters) • Double leg jumps backward (2x 14.5 meters) • Double leg jumps side to side and forward (2x 14.5 meters) • Double leg jumps side to side and backward (2x 14.5 meters) • Alternate double leg jumps forward to backward on the whistle (2x 14.5 meters) • Double leg jumps side to side and alternating forward and backward directions on the whistle (2x 14.5 meters) • Shuffling moderate pace left (2x 14.5 meters) • Shuffling moderate pace right (2x 14.5 meters)
Practice/competition.........cool down and stretch

Table 13

Dexterity Protocol: Week #4

Dynamic warm-up and stretch
• Skipping forward (2x 29 meters) • Backskip (2x 29 meters) • Crossover sideskip (2x 29 meters) • Shuffling moderate pace left (2x 29 meters) • Shuffling moderate pace right (2x 29 meters) • Carioca moderate pace w/ moderate gait amplitude (2x 29 meters) • Carioca moderate pace w/ large gait amplitude (2x 29 meters) • Carioca moderate pace w/ small gait amplitude (2x 29 meters) • Alternate shuffle right and left w/ easy pace and change direction on the whistle (2x 29 meters) • Alternate carioca right and left w/ easy pace and change direction on the whistle (2x 29 meters) • Alternate shuffle right and left easy pace on the single whistle; shuffle in the same direction w/ 180 degree turn on the double whistle (3x 29 meters) • Alternate carioca right and left easy pace on the single whistle; carioca in the same direction w/ 180 degree turn on the double whistle (3x 29 meters)
Practice/competition.........cool down and stretch

Table 14

Dexterity Protocol: Week #5

Dynamic warm-up and stretch
• Alternate skip/backskip.......easy pace................ (29 meters on the whistle) • Alternate skip/crossover sideskip......easy pace......(29 meters on the whistle) • Alternate backskip/crossover sideskip......easy pace......(29 meters on the whistle) • Alternate skip/backskip on single whistle......crossover sideskip on double whistle (29 meters) • Alternate shuffle right/left and change direction on the whistle (2x 29 meters) • Alternate carioca right/left and change direction on the whistle (2x 29 meters) • Alternate shuffle right and left easy pace on the single whistle; shuffle in the same direction w/ 180 degree turn on the double whistle (3x 29 meters) • Alternate carioca right and left easy pace on the single whistle; carioca in the same direction w/ 180 degree turn on the double whistle (3x 29 meters) • Single leg hops forward; jog on whistle (2x 14.5 meters) • Double leg jumps forward jog on whistle (2x 14.5 meters) • Single leg hops backward jog on whistle (2x 14.5 meters) • Double leg jumps backward jog on whistle (2x 14.5 meters)
Practice/competition.........cool down and stretch

Table 15

Dexterity Protocol: Week #6

Dynamic warm-up and stretch
• Double leg jumps in place; land "quiet" (5 x 5) • Alternate skip/backskip.................. (29 meters on the whistle) • Alternate skip/crossover sideskip......(29 meters on the whistle) • Alternate backskip/crossover sideskip......(29 meters on the whistle) • Alternate skip/backskip on single whistle......crossover sideskip on double whistle (29 meters) • Alternate shuffle right and left w/ change of direction on the whistle (2x 29 meters) • Alternate carioca right and left w/ change of direction on the whistle (2x 29 meters) • Alternate shuffle right and left on the single whistle; shuffle in the same direction w/ 180 degree turn on the double whistle (3x 29 meters) • Alternate carioca right and left on the single whistle; carioca in the same direction w/ 180 degree turn on the double whistle (3x 29 meters) • Single leg hops forward; jog on whistle (2x 14.5 meters) • Double leg jumps forward jog on whistle (2x 14.5 meters) • Single leg hops backward jog on whistle (2x 14.5 meters) • Double leg jumps backward jog on whistle (2x 14.5 meters)
Practice/competition.........cool down and stretch

APPENDIX E

Participant Body Segment Parameters for Inverse Dynamics Procedure

Table 16

Whole Body and Lower Extremity Anthropometric Parameters of Stature, Body Mass, and the Right Thigh, Shank, and Foot for All Participants

Subject	Stature (cm)	Mass (kg)	Right Thigh Length (cm)	Right Shank Length (cm)	Right Foot Length (cm)
E1	157.2	55.5	41.5	34	23
E2	167.5	51.5	42.5	38.6	23.5
E2	165.4	49.8	40.5	36.6	23.8
E4	174.9	85.4	45.5	39.8	25.5
C1	174.3	83.9	43.5	38.9	24.5
C2	155.6	50.2	41	38.6	24.1

Note. E = experimental group.
C = control group.

APPENDIX F

MATLAB Source Code for Inverse Dynamics Procedures

```
no% Converts ANC captured from MAC to force data for both leg & foot

% work on:
% baseline error at beginning used (but can change over time!)
% header names on saved files
%-----------------------------------------------------------------------
% matrices named in square brackets to provide output
function []=TonyJump; %[ZYsum,XCPsum]=AMTI_FP;
clear all
close all
%-----------------------------------------------------------------------
% start menu
prompt={'Enter data path of key time file:','Enter name of key time file (e.g.
keytimes.txt):',...
      'Kinematics Sampling frequency','Kinematics Smoothing cutoff frequency (use 0 if
already smoothed)',...
      'Force smoothing (use 0 if already smoothed)','Force plate sampling frequency',....
      'Enter start trial (from 1 to n)','Enter end trial (from 2 to n)',...
      'Inverse dynamics smoothing cutoff frequency (use 0 if already smoothed',...
      'Save data? (yes)','Enter output directory','Output suffix'};
title='Inverse dynamics for 2 joints';
lines=1;
def={'P:\keyfiles\','keyfile_kpost34.txt','120','0','0','1200','1','1','0','no','P:\Output\','_kpost'
};
% Change 3 things: keyfile name; end row (e.g. 34); output name (e.g. % kpost)
% keyfile_kpost34.txt keyfile_kpre28.txt
% keyfile_lpost31.txt keyfile_lpre24.txt keyfile_rpost33.txt keyfile_rpre26.txt
% keyfile072204.txt 176

answer=inputdlg(prompt,title,lines,def);
fileloc=char(answer{1});
keyfile=char(answer{2});
SF=str2num(answer{3});
CF=str2num(answer{4});
CFfp=str2num(answer{5});
SFfp=str2num(answer{6});
starttrial=str2num(answer{7});
endtrial=str2num(answer{8});
CFid=str2num(answer{9});
savedata=char(answer{10});
outputdir=char(answer{11});
outsuffix=char(answer{12});

% Force plate settings
```

```
gain=4000;
voltage=10;
range=10;
mat=0.01;

%----------------------------------------------------------------------
% set data path
data_path = [fileloc];
eval(['cd ' data_path]);
[filedir subdir2 subdir3 subdir4 subdir5 horse horse2 horse3 horse4 trialno...
   suffix startt endt FPfile cond BM prepost] ...
   =textread(keyfile,'%s %s %s %s %s %s %s %s %s %d %s %d %d %s %s %d %s');
[nr1 nc1]=size(filedir);

%----------------------------------------------------------------------
% define output names before loop
sumfx=[];sumfy=[];sumfz=[];kneeall=[];ankleall=[];
JFxankle=[];JFyankle=[];Mankle=[];JFxknee=[];JFyknee=[];Mknee=[];
RKneeDis=[];
%----------------------------------------------------------------------
for i=starttrial:endtrial % end at bottom
fileloc=char(strcat(filedir(i,:),subdir2(i,:),subdir3(i,:),subdir4(i,:),subdir5(i,:)));
fileloc=strrep(fileloc,'none',''); %replaces text
trcfile=char(strcat(horse(i,:),horse2(i,:),horse3(i,:),horse4(i,:),...
   num2str(trialno(i,:)),suffix(i,:),'.trc'));
trcfile=strrep(trcfile,'none',''); %replaces text
data_path = [fileloc];
eval(['cd ' data_path]);

%----------------------------------------------------------------------
% Calibration matrix
% Columns Fx, Fy, Fz, Mx, My, Mz
% Rows Vx, Vy, Vz, VMx, VMy, VMz
CalVx=[11.8317 -0.041 -0.1199 -0.0981 -0.2502 0.3295];
CalVy=[0.0179 12.0391 -0.2026 0.0599 -0.0271 0.1275];
CalVz=[-0.1007 0.0781 49.185 0.1032 0.0623 0.1413];
CalMx=[0.0175 0.035 -0.0064 11.1411 -0.0553 0.045];
CalMy=[0.0345 -0.0525 -0.0381 -0.043 7.8813 0.0368];
CalMz=[-0.0219 -0.0632 -0.1123 -0.0877 0.0567 4.2467];
% Calibration formula (Newtons per bit)
Nperbit=1/((4096/(2*range))*(gain*voltage*0.000001));

% Centre of force plate correction
offsetx=-0.000765;
offsety=0.000097;
offsetz=-0.059116-mat;
```

```
%-----------------------------------------------------------------------
% Reads in *.anc file
[Time Vx Vy Vz VMx VMy VMz EMG1 EMG2 EMG3 EMG4 EMG5 EMG6 EMG7
EMG8 Blank]...

=textread(char(FPfile(i)),'%f%d%d%d%d%d%d%s%s%s%s%s%s%s%s%s','headerlines'
,11);
RawF=[Vx Vy Vz VMx VMy VMz];

%-----------------------------------------------------------------------
% smoothing (4th order Butterworth. Not damped)

SmoothV=RawF;
if CFfp>0
SmoothV=Butterfilter(CFfp, SFfp, RawF);
end

% [Bb,Ab] = butter(2,CFfp/(SFfp/2),'low') ;
% smoothtemp=filtfilt(Bb,Ab,RawF);
% SmoothV=smoothtemp;

%-----------------------------------------------------------------------
Startfp=(startt(i)*(SFfp/SF))-1; %-1 needed to account for header rows
Endfp=(endt(i)*(SFfp/SF))-1;

SmoothV=SmoothV(Startfp:Endfp,:);

% Baseline correction
OffsetFx=mean(RawF(Startfp-50:Startfp-1,1))*Nperbit;
OffsetFy=mean(RawF(Startfp-50:Startfp-1,2))*Nperbit;
OffsetFz=mean(RawF(Startfp-50:Startfp-1,3))*Nperbit;
OffsetMx=mean(RawF(Startfp-50:Startfp-1,4))*Nperbit;
OffsetMy=mean(RawF(Startfp-50:Startfp-1,5))*Nperbit;
OffsetMz=mean(RawF(Startfp-50:Startfp-1,6))*Nperbit;

%Data: combines smoothing/calibration/baseline correction/plate centre offset
FVxCalVx=Nperbit*(SmoothV(:,1).*CalVx(:,1)+SmoothV(:,2).*CalVx(:,2)+SmoothV(:,
3).*CalVx(:,3)...

+SmoothV(:,4).*CalVx(:,4)+SmoothV(:,5).*CalVx(:,5)+SmoothV(:,6).*CalVx(:,6))...
    +OffsetFx;
FVyCalVy=Nperbit*(SmoothV(:,1).*CalVy(:,1)+SmoothV(:,2).*CalVy(:,2)+SmoothV(:,
3).*CalVy(:,3)...

+SmoothV(:,4).*CalVy(:,4)+SmoothV(:,5).*CalVy(:,5)+SmoothV(:,6).*CalVy(:,6))...
```

```
    +OffsetFy;
FVzCalVz=Nperbit*(SmoothV(:,1).*CalVz(:,1)+SmoothV(:,2).*CalVz(:,2)+SmoothV(:,
3).*CalVz(:,3)...

+SmoothV(:,4).*CalVz(:,4)+SmoothV(:,5).*CalVz(:,5)+SmoothV(:,6).*CalVz(:,6))...
    +OffsetFz;
MVxCalMx=Nperbit*(SmoothV(:,1).*CalMx(:,1)+SmoothV(:,2).*CalMx(:,2)+SmoothV
(:,3).*CalMx(:,3)...

+SmoothV(:,4).*CalMx(:,4)+SmoothV(:,5).*CalMx(:,5)+SmoothV(:,6).*CalMx(:,6))...
    -FVyCalVy*offsetz-FVzCalVz*offsety+OffsetMx;
MVyCalMy=Nperbit*(SmoothV(:,1).*CalMy(:,1)+SmoothV(:,2).*CalMy(:,2)+SmoothV
(:,3).*CalMy(:,3)...

+SmoothV(:,4).*CalMy(:,4)+SmoothV(:,5).*CalMy(:,5)+SmoothV(:,6).*CalMy(:,6))...
    +FVxCalVx*offsetz+FVzCalVz*offsetx+OffsetMy;
MVzCalMz=Nperbit*(SmoothV(:,1).*CalMz(:,1)+SmoothV(:,2).*CalMz(:,2)+SmoothV(
:,3).*CalMz(:,3)...

+SmoothV(:,4).*CalMz(:,4)+SmoothV(:,5).*CalMz(:,5)+SmoothV(:,6).*CalMz(:,6))...
    -FVxCalVx*offsety-FVyCalVy*offsetx+OffsetMz;
ForceN=[FVxCalVx FVyCalVy FVzCalVz MVxCalMx MVyCalMy MVzCalMz];

%-------------------------------------------------------------------------
% interpolate from 1 in increments of r/101 to size (i.e. make 101 length)
ForceTemp=ForceN;
[nr nc]=size(ForceTemp);
newsize=101;
% to keep first/last same as orginal use 1:(nr-1)/(newsize-1):nr
Force101=[interp1(ForceTemp,1:(nr-1)/(newsize-1):nr,'spline')]; %add ' at end if only 1

sumfx=[sumfx,Force101(:,1)];
sumfy=[sumfy,Force101(:,2)];
sumfz=[sumfz,Force101(:,3)];

ax=-Force101(:,5)./Force101(:,3);
ay=Force101(:,4)./Force101(:,3);

dataforceall=[Force101(:,1),Force101(:,2),Force101(:,3)]; % use x in second column
dataforceall(:,4)=ax(:,:)+0.336; % only need 1 offset correction for 2D (both for 3D)
dataforceall(:,5)=ay(:,:); % -0.991118;

% improve end values of ay
dataforceall(1,4)=dataforceall(2,4)-dataforceall(3,4)+dataforceall(2,4);
dataforceall(101,4)=dataforceall(100,4)-dataforceall(99,4)+dataforceall(100,4);
```

```
% %-----------------------------------------------------------------------
% loads kinematics
rawkine=dlmread([trcfile],'\t',[startt(i)+5 2 endt(i)+5 88]);
% converts mm to m
rawkine=rawkine/1000;
[nr nc]=size(rawkine);
KineTemp=rawkine;

% smoothing (4th order Butterworth. Not damped)
if CF>0
Smoothkine=Butterfilter(CF, SF, rawkine);
KineTemp=Smoothkine; % can add dataraw to clipboard
end

% interpolate from 1 in increments of r/101 to size (i.e. make 101 length)
newsize=101;
% to keep first/last same as orginal use 1:(nr-1)/(newsize-1):nr
Kine101=[interp1(KineTemp,1:(nr-1)/(newsize-1):nr,'spline')]; %add ' at end if only 1

% new SF
newSF=SF/(nr/newsize);

%-----------------------------------------------------------------------
%Calculate segment angles in 3D (make, e.g, z zeros for 2D)
kneeraw = [Kine101(:,10) Kine101(:,11) Kine101(:,12) Kine101(:,73) Kine101(:,74)
Kine101(:,75)...
   Kine101(:,73) Kine101(:,74) Kine101(:,75) Kine101(:,76) Kine101(:,77)
Kine101(:,78)];
kneea=angle2d(kneeraw); %calling function angle2d
kneeall=[kneeall,kneea];
radkneea=kneea/(180/pi);

% V_knee   V_ankle              V_shankcom  V_midtoe    V_footcom
% 73  74    75    76    77     78     79    80    81    82    83    84
      85    86    87

ankleraw = [Kine101(:,73) Kine101(:,74) Kine101(:,75) Kine101(:,76) Kine101(:,77)
Kine101(:,78)...
   Kine101(:,76) Kine101(:,77) Kine101(:,78) Kine101(:,82) Kine101(:,83)
Kine101(:,84)];
anklea=angle2d(ankleraw);
ankleall=[ankleall,anklea];
radanklea=anklea/(180/pi);

% Simpler 2D angle method
```

```
% thighsa=180/pi*(pi-(atan2((Kine101(:,12)-Kine101(:,15)),(Kine101(:,10)-
Kine101(:,13)))));
% shanksa=180/pi*(pi-(atan2((Kine101(:,15)-Kine101(:,21)),(Kine101(:,13)-
Kine101(:,19)))));
% kneea=180-(thighsa-shanksa);
%------------------------------------------------------------------------
%Input parameters for knee displacement
RKneeDis=[RKneeDis,Kine101(:,73)];

%------------------------------------------------------------------------
% Input parameters for inverse dynamics
diftime=1/newSF; %new sampling frequency

for jjj=1:2
   switch jjj
case 1
% marker1=85; % ankle COM
forcepoint=dataforceall(:,4); % ay force plate
originheight=0; %mean(Kine101(:,84));
x1=Kine101(:,77); % ankle
y1=Kine101(:,78); % ankle
segmass=repmat(0.021*BM(i),101,1);
minertia=repmat(0.475,101,1); %0.004

jangle=radanklea;
jointforces(:,1)=dataforceall(:,1); % braking must be -ve? x is used for TonyJump
jointforces(:,2)=dataforceall(:,3);
premoment=repmat(0,101,1);

% COM ankle location
comx=Kine101(:,86);
comy=Kine101(:,87);

case 2
% marker1=79; % shank COM
forcepoint=Kine101(:,77); % ankle
originheight=Kine101(:,78); %ankle
x1=Kine101(:,74); % knee
y1=Kine101(:,75); % knee
segmass=repmat(0.053*BM(i),101,1);
minertia=repmat(0.302,101,1); %0.065

jangle=radkneea;
jointforces(:,1)=JFxankle(:,i);
jointforces(:,2)=JFyankle(:,i);
premoment=Mankle(:,i);
```

```
% COM location
comx=Kine101(:,80);
comy=Kine101(:,81);

   end
%------------------------------------------------------------------------
% COM accelerations
segcom=[comx,comy,jangle];
accels=repmat(0,101,3);
accels(2:100,:)=(segcom(3:101,:)+segcom(1:101-2,:)-2*segcom(2:101-1,:))/(diftime^2);
% finds first 1 and last 1 and adds
comr1=(accels(2,:)-accels(3,:))+accels(2,:);
comr2=(accels(100,:)-accels(99,:))+accels(100,:);
segcomacc=[comr1;accels(2:100,:);comr2];
jointaccx=segcomacc(:,1);
jointaccy=segcomacc(:,2);
angacc=segcomacc(:,3);

%------------------------------------------------------------------------
% JointFx=jointforces(:,1)-segmass.*jointaccx; % Winter book
% JointFy=jointforces(:,2)-segmass.*jointaccy-segmass*9.81; % Winter book
JointFx=-(segmass.*jointaccx-jointforces(:,1)); % Enoka book
JointFy=-(segmass.*jointaccy-segmass*-9.81-jointforces(:,2)); % Enoka book
   %------------------------------------------------------------------------
     % smoothing joint force
   if CFid>0
   JointFx=Butterfilter(CFid, newSF, JointFx);
   JointFy=Butterfilter(CFid, newSF, JointFy);
   end

   %------------------------------------------------------------------------
JointMoment=premoment...
   +(abs(x1-forcepoint).*jointforces(:,2))...
   -(abs(y1-originheight).*jointforces(:,1))...
   -(abs(x1-comx).*segmass*-9.81)...
   +minertia.*angacc...
   +segmass.*jointaccx.*abs(y1-comy)...
   +segmass.*jointaccy.*abs(x1-comx); % Enoka book

%------------------------------------------------------------------------
% output
switch jjj
case 1
JFxankle=[JFxankle,JointFx];
JFyankle=[JFyankle,JointFy];
```

```
Mankle=[Mankle,JointMoment];

case 2
JFxknee=[JFxknee,JointFx];
JFyknee=[JFyknee,JointFy];
Mknee=[Mknee,JointMoment];
end

end % from for at begin of inverse dynamics
%------------------------------------------------------------------------
% end % from switch at begin of inverse dynamics
%
=================================================================
==========

i
end %from beginning
figure
subplot(3,2,1)
plot(sumfx); xlabel('Fx'); xlim([0 100])
subplot(3,2,3)
plot(sumfz); xlabel('Fz'); xlim([0 100])
subplot(3,2,5)
plot(sumfy); xlabel('Fy'); xlim([0 100])
subplot(3,2,4)
plot(kneeall); xlabel('Knee angle'); xlim([0 100])
% subplot(3,2,2)
% none
subplot(3,2,6)
plot(ankleall); xlabel('Ankle angle'); xlim([0 100])

figure
subplot(3,2,1)
plot(JFxankle); xlabel('JFxankle'); xlim([0 100])
subplot(3,2,2)
plot(JFxknee); xlabel('JFxknee'); xlim([0 100])
subplot(3,2,3)
plot(JFyankle); xlabel('JFyankle'); xlim([0 100])
subplot(3,2,4)
plot(JFyknee); xlabel('JFyknee'); xlim([0 100])
subplot(3,2,5)
plot(Mankle); xlabel('Mankle'); xlim([0 100])
subplot(3,2,6)
plot(Mknee); xlabel('Mknee'); xlim([0 100])

figure
```

```
subplot(2,1,1)
plot(RKneeDis); xlabel('LKneeDis'); xlim([0 100])
subplot(2,1,2)
plot(RKneeDis); xlabel('RKneeDis'); xlim([0 100])

%-----------------------------------------------------------------------------------------------
% saves data
switch savedata
   case 'yes'
      dlmwrite([outputdir 'sumFx' outsuffix '.txt'],sumfx,'\t');
      dlmwrite([outputdir 'sumFz' outsuffix '.txt'],sumfz,'\t');
      dlmwrite([outputdir 'kneeA' outsuffix '.txt'],kneeall,'\t');
      dlmwrite([outputdir 'ankleA' outsuffix '.txt'],ankleall,'\t');
      dlmwrite([outputdir 'Mankle' outsuffix '.txt'],Mankle,'\t');
      dlmwrite([outputdir 'Mknee' outsuffix '.txt'],Mknee,'\t');
      dlmwrite([outputdir 'RKneeDis' outsuffix '.txt'],RKneeDis,'\t');
end
% sumfx=[];sumfy=[];sumfz=[];kneeall=[];ankleall=[];
% JFxankle=[];JFyankle=[];Mankle=[];JFxknee=[];JFyknee=[];Mknee=[];

%==========================================================
============
% functions (1 of 1)
%==========================================================
============
% smoothing (4th order Butterworth. Not damped)
% Input: SF, CF and Rawdata
% Output: Smoothdata
function [Smoothdata]=Butterfilter(CF, SF, Rawdata)

[nrows ncols]=size(Rawdata);
CFa=CF/0.802; % Adjusts 2nd order for 4th order (i.e. n=2 for second pass) using:
%=CF/0.435 i.e. SQRT(2^(1/(2*n))-1) for damped. Also, later Wc=SC*2
%=CF/0.802 i.e. (2^(1/n)-1)^0.25 for undamped. Also, later Wc=SC*sqrt(2)
SC=tan(pi*CFa/SF);
Wc=SC*sqrt(2);  %Undamped is Wc=SC*sqrt(2)  If damped is Wc=SC*2
M=1+Wc+SC^2;
a0=SC^2/M;
a1=2*a0;
a2=a0;
b1=2*(1-SC^2)/M;
b2=(Wc-SC^2-1)/M;
Smoothfirst=zeros(nrows,ncols);
for r=3:nrows
Smoothfirst(r,:)=Rawdata(r,:)*a0+Rawdata(r-1:r-1,:)*a1+Rawdata(r-2:r-2,:)*a2...
   +Smoothfirst(r-1:r-1,:)*b1+Smoothfirst(r-2:r-2,:)*b2;
```

```
end
Smoothreverse=flipud(Smoothfirst);
Smoothsecond=Smoothreverse;
for r=3:nrows
Smoothsecond(r,:)=Smoothreverse(r:r,:)*a0+Smoothreverse(r-1:r-
1,:)*a1+Smoothreverse(r-2:r-2,:)*a2...
  +Smoothsecond(r-1:r-1,:)*b1+Smoothsecond(r-2:r-2,:)*b2;
end
Smoothdata=flipud(Smoothsecond);

%=============================================================
============
% functions (2)
%=============================================================
============
% Modified so that input is 12 variables, so calculates 3D angle

function [alpha]=angle2d(data)
% function [alpha]=angle2d(data)
% Description:  Calculates the angle between 2 vectors (given by pairs of points)
%           in 2 dimensions.
% Input:      data:   data = [P1x P1y P2x P2y P3x P3y P4x P4y]
%           Note that "data" can have several rows (e.g. different time
%               points).
% Output:     alpha:  angle (in deg) between the vectors P1-P2 and P3-P4
% Author:     Christoph Reinschmidt, HPL, The University of Calgary
% Date:       October, 1994
% Last Changes: November 28, 1996
% Version:    1.0

if ~(size(data,2)==12)
  disp('Error: # of rows of input matrix has to be 12!')
  return;
end

% % "assigning" zero to the z-coordinates
% tmp=data; data=[]; data(:,[1 2 4 5 7 8 10 11])=tmp;
% data(size(data,1),12)=[0];

r1=data(:,1:3); r2=data(:,4:6); r3=data(:,7:9); r4=data(:,10:12);
v1=r2-r1; v2=r4-r3;

% Preassigning alpha to speed up program
alpha=zeros(size(v1,1),1);

for i=1:size(v1,1);
```

```
 vect1=[v1(i,:)]'; vect2=[v2(i,:)]';
 x=cross(vect1,vect2);
 alphacos=rad2deg(acos(sum(vect1.*vect2)/(norm(vect1)*norm(vect2)))); % calling a
function
 y=x(3,1);
%  % Determining if alpha b/w 0 and pi or b/w -pi and 0
%  if sign(y)==-1;  alphacos=-alphacos; end
 alpha(i,:)=[alphacos];
end

%=====================================================================
============
% functions (3)
%=====================================================================
============
function [out]=rad2deg(in)

% function [out]=rad2deg(in)
% Description:        Conversion of radians to degrees applied to the entire matrix
% Input:       in (values in radians)
% Output:      out (values in degrees)
% Author:      Christoph Reinschmidt, HPL, The University of Calgary
% Date:               October, 1994
% Last Changes:       November 29, 1996
% Version:     1.0

out=in.*(180/pi);
%=====================================================================
============
```

APPENDIX G

Participant Mean Value Data for the Dependent Variables

Table 17

Pre-intervention Mean Values for the Dependent Variables of Each Subject during Landing with Anticipated Conditions

Subject Identification	*Mean Peak Ground Reaction Force on Impact*[a]	*Mean Peak Knee Flexion Angular Displacement on Impact (degrees)*	*Mean Time to Peak Knee Flexion Angular Displacement on Impact (s)*	*Mean Peak Right Knee Extensor Moment on Impact*[b]
E1	6.8	79.8	0.30	3.8
E2	8.0	64.7	0.19	4.5
E3	11.2	91.2	0.27	4.5
E4	5.6	75.3	0.23	2.4
C1	6.2	71.8	.20	2.3
C2	8.0	62.7	.12	4.6

a = Ground reaction force values normalized by body mass.
b = Knee extensor moment values normalized by body mass.
Note. E = experimental group.
C = control group.

Table 18

Pre-intervention Mean Values for the Dependent Variables of Each Subject during Landing with Unanticipated Conditions

Subject Identification	*Mean Peak Ground Reaction Force on Impact*[a]	*Mean Peak Knee Flexion Angular Displacement on Impact (degrees)*	*Mean Time to Peak Knee Flexion Angular Displacement on Impact (s)*	*Mean Peak Right Knee Extensor Moment on Impact*[b]
E1	20.1	54.8	0.16	5.4
E2	18.9	57.3	0.20	4.0
E3	18.2	74.4	0.22	4.7
E4	15.3	70.7	0.19	4.0
C1	13.5	72.3	0.19	3.8
C2	18.5	38.9	0.13	7.5

a = Ground reaction force values normalized by body mass.
b = Knee extensor moment values normalized by body mass.
Note. E = experimental group.
C = control group.

Table 19

Post Intervention Mean Values for the Dependent Variables of Each Subject during Landing with Anticipated Conditions

Subject Identification	*Mean Peak Ground Reaction Force on Impact*[a]	*Mean Peak Knee Flexion Angular Displacement on Impact (degrees)*	*Mean Time to Peak Knee Flexion Angular Displacement on Impact (s)*	*Mean Peak Right Knee Extensor Moment on Impact*[b]
E1	9.4	70.9	0.19	2.3
E2	13.6	71.4	0.21	3.3
E3	19.2	74.0	0.19	4.1
E4	9.4	77.6	0.22	2.8
C1	7.2	64.3	0.21	2.3
C2	6.6	66.4	0.09	5.6

a = Ground reaction force values normalized by body mass.
b = Knee extensor moment values normalized by body mass.
Note. E = experimental group.
C = control group.

Table 20

Post Intervention Mean Values for the Dependent Variables of Each Subject during Landing with Unanticipated Conditions

Subject Identification	*Mean Peak Ground Reaction Force on Impact*[a]	*Mean Peak Knee Flexion Angular Displacement on Impact (degrees)*	*Mean Time to Peak Knee Flexion Angular Displacement on Impact (s)*	*Mean Peak Right Knee Extensor Moment on Impact*[b]
E1	24.3	47.9	0.14	6.8
E2	17.0	60.5	0.21	3.6
E3	26.7	80.4	0.27	5.1
E4	17.3	70.6	0.22	4.6
C1	17.0	58.0	0.18	4.1
C2	20.8	55.7	0.15	6.5

a = Ground reaction force values normalized by body mass.
b = Knee extensor moment values normalized by body mass.
Note. E = experimental group.
C = control group.

Table 21

Mean Peak Ground Reaction Force on Impact[a]

Subject Identification	*Number of Trials*	*Pre-intervention*	*Number of Trials*	*Post intervention*
E1	9	20.1	7	24.3
E2	8	18.9	10	17.0
E3	4	18.2	3	26.7
E4	9	15.3	11	17.3
C1	10	13.5	9	17.0
C2	10	18.5	11	20.8

a = Ground reaction force values normalized by body mass.
Note. E = experimental group.
C = control group.

Table 22

Mean Peak Knee Flexion on Landing

Subject Identification	*Number of Trials*	*Pre-intervention (degrees)*	*Number of Trials*	*Post intervention (degrees)*
E1	9	54.8	12	47.9
E2	8	57.3	11	60.5
E3	4	74.4	9	80.4
E4	9	70.7	11	70.6
C1	10	72.3	9	58.0
C2	10	38.9	12	55.7

Note. E = experimental group.
C = control group.

Table 23

Mean Time to Peak Knee Flexion on Impact

Subject Identification	*Number of Trials*	*Pre-intervention (seconds)*	*Number of Trials*	*Post intervention (seconds)*
E1	9	0.16	12	0.14
E2	8	0.20	11	0.21
E3	4	0.22	9	0.27
E4	9	0.19	11	0.22
C1	10	0.19	9	0.18
C2	10	0.13	12	0.15

Note. E = experimental group.
C = control group.

Table 24

Mean Peak Right Knee Extensor Moment[a]

Subject Identification	*Number of Trials*	*Pre-intervention (N-m)*	*Number of Trials*	*Post intervention (N-m)*
E1	9	5.4	12	6.8
E2	8	4.0	10	3.6
E3	4	4.7	9	5.1
E4	9	4.0	11	4.6
C1	10	3.8	9	4.1
C2	10	7.5	12	6.5

a = Right knee extensor moment values normalized by body mass.
Note. E = experimental group.
C = control group.

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