2009

CHANGES IN LONGITUDINALLY ASSESSED BIOMECHANICAL PARAMETERS RELATED TO INCREASED RISK OF ANTERIOR CRUCIATE LIGAMENT (ACL) INJURIES IN ADOLESCENT FEMALE AND MALE ATHLETES

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ABSTRACT OF DISSERTATION

Kevin Ray Ford

The Graduate School

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ABSTRACT OF DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Education at the University of Kentucky

By
Kevin Ray Ford

Lexington, Kentucky

Director: Dr. Robert Shapiro, Professor of Kinesiology and Health Promotion

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Females suffer anterior cruciate ligament (ACL) injuries at a 2 to 10-fold greater rate compared to male athletes participating in similar sports. Altered movement patterns and inadequate knee stiffness are two interrelated factors that may increase ACL injury risk. Onset of these neuromuscular risk factors may coincide with the rapid adolescent growth that results in the divergence of a multitude of neuromuscular parameters between sexes. The overall purpose of this dissertation was to determine if neuromuscular ACL injury risk factors in female athletes increase following rapid growth and development compared to males. Male and female athletes were tested with three-dimensional motion analysis techniques during a drop vertical jump over two consecutive years to determine if ACL injury risk factors increased. Pubertal females showed a significant longitudinal increase in knee abduction angle compared to post-pubertal females and both male groups. The increase in knee abduction angle appeared to remain consistent, as the post pubertal female cohort had greater overall knee abduction compared to post-pubertal males. Similar results were found with a greater magnitude of knee abduction moment in post-pubertal females compared to males. Males and females increased ankle, knee and hip active stiffness from the first to second year of testing. Ankle and hip stiffness were increased significantly more in the pubertal group compared to post-pubertal. Sex and maturational group differences were found in hip and ankle joint stiffness. Post-pubertal males had significantly greater hip stiffness than the other groups (even when normalized to body mass). This indicates that post-pubertal males utilized a different neuromuscular strategy during landing. Males had a significantly greater increase from year to year in vertical jump height compared to females. Vertical jump height is often related to a measure of whole body power and indicates that males had a significant neuromuscular spurt compared to females. Early puberty appears to be a critical phase related to the divergence of increased ACL injury risk factors. Injury prevention programs that focus on neuromuscular training may be beneficial to help address the development of ACL injury risk factors that occur in female athletes during maturation.

KEYWORDS: Anterior Cruciate Ligament, knee injury prevention, female, sex differences, knee abduction

Kevin Ray Ford

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This dissertation is dedicated to my wife, Heather, and our two daughters, Hannah and Ally, for supporting me throughout this entire process. I thank Heather for her love and continual dedication. Hannah and Ally, thank you for keeping me focused on what is truly important in life – Faith and Family! I also thank you both for your understanding of the time Dad has had to spend away from home.

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Chapter 1. Introduction

Females in pivoting and jumping sports suffer anterior cruciate ligament (ACL) injuries at a 2 to 10-fold greater rate compared to male athletes participating in the same high-risk sports.[1-6] The combination of this greater susceptibility and a 10-fold increase in the female sports population since the inception of Title IX has resulted in a dramatic increase in the number of ACL injuries in females.[5] ACL injury conservatively costs between $17,000-$25,000 per injury for surgery and rehabilitation.[7, 8] The high number and cost of these ACL injuries is accompanied by the potential loss of entire seasons of sports participation, scholarship funding, lowered academic performance, long term disability and significantly greater risk of osteoarthritis.[9, 10] The mechanisms responsible for the sex differences in these debilitating sports injuries have been investigated with a variety of methodology.[7, 11-18]

Factors underlying the injury rate disparity in females compared to males have been categorized into several general theories: anatomical, hormonal and neuromuscular. Anatomical risk factors that have been proposed include anthropometric differences, increased body mass index, increased Q-angle, narrower femoral notch and increased hypermobility or laxity in female athletes. Cyclic changes in hormone levels may be possible contributors to the increased injury rates in female athletes.[19] The experimental findings regarding the influence of hormones on injury risk are limited and remain controversial.[20] Biomechanical or neuromuscular differences between sexes have also been postulated to play a role in ACL injury risk. Neuromuscular control of a joint specifically relates to the activation of the dynamic restraints surrounding a joint in response to sensory stimuli.[20, 21] Neuromuscular mechanisms likely play a critical role in the sex differences found in ACL injuries.[20] This is supported by evidence that injury prevention programs that focused on neuromuscular control of the lower extremity have reduced non-contact ACL injuries in female athletes.[22-24]

Decreased neuromuscular control of the lower extremity may lead to increased knee abduction loads and strain on the knee ligaments.[25-28] Though there likely are multiple factors that underlie the differences in ACL injury rates in male and female athletes, neuromuscular control may be the greatest contributor to injury risk and the most modifiable factor.[29] There is currently no evidence to suggest that a sex difference in ACL injury rate is found in athletes prior to the adolescent growth spurt.[30-33] However, following their growth spurt, female athletes have higher rates of knee sprains, which continues into maturity.[34] Therefore, it appears that females may develop certain risk factors during maturation that may place them at greater risk of injury compared to males.

Statement of the Problem

Altered movement patterns and inadequate knee stiffness are two interrelated factors that may increase ACL injury risk.[35] Onset of these neuromuscular risk factors may coincide with the rapid adolescent growth that results in the divergence of a multitude of neuromuscular parameters between sexes. Thus, it has been hypothesized that following the adolescent growth spurt, increased body mass and height of the center of mass, in the absence of increases in strength and power, lead to altered movement patterns and inadequate muscle stiffness.[36, 37] Therefore, the timing of adolescent growth may be the critical phase of growth and development related to sex differences in ACL injury risk. However, at this time the effect of rapid growth and development in females on ACL risk factors is unknown.

Significance of the study

This proposal will lead to advances in the understanding of the mechanisms and prevention of ACL injuries in female athletes. ACL injury prevention programs would be more effective if both the timing of the onset and the mechanisms that underlie the increased risk were identified. The Department of Health and Human Services recommends that women, both young and old, remain active to maintain optimal health.[38] Reduction of female injury rates would potentially allow thousands of females annually to continue the health benefits of sports participation and to avoid the long-term complications of osteoarthritis, which occurs with a 10 to 100-fold greater incidence in ACL-injured than in uninjured athletes.[39, 40]

Purpose

The overall purpose of this dissertation was to identify if neuromuscular ACL injury risk factors in female athletes increase following rapid growth and development compared to males. Specifically, the projects are directed towards answering the following research questions: 1) Does the onset of neuromuscular risk factors in female athletes occur during rapid adolescent growth? 2) Does an absence of increased neuromuscular performance measures correlate to the development of these risk factors?

Chapter 2 presents the theoretical rationale for how we designed the investigation to answer the previously stated research questions. Included is a detailed strategy that can be utilized for the development of sports injury prevention strategies. Injury mechanisms and risk factors are introduced and supported with the published literature. We specifically present three inter-related Specific Aims that relate to increased risk of female ACL knee injuries compared to males. The three specific aims are addressed in Chapters 3, 4 and 5.

Chapter 3 is aimed at the determination of the specific timed onset of neuromuscular risk factors related to abnormal movement patterns increase in females, but not males, during the adolescent growth spurt. We first hypothesized that during adolescent growth, pubertal females would demonstrate longitudinal increases in knee abduction motion and moments compared to pubertal males. Secondly, we hypothesized that post-pubertal females, following pubertal growth, would have significantly greater knee abduction motion and moments compared to post-pubertal males.

The fourth Chapter's specific aim is to determine if the neuromuscular risk factors related to inadequate knee stiffness diverge between the sexes during the adolescent growth spurt. The first hypothesis tested was that during the rapid adolescent growth spurt, pubertal males would have increases in knee stiffness while pubertal females would not. The second hypothesis was that post-pubertal females would have significantly lower knee joint stiffness compared to post-pubertal males.

The specific aims of Chapter 5 were primarily to identify longitudinal neuromuscular performance differences between sex and maturational groups and secondly, to investigate the relationships between altered movement patterns, joint stiffness and neuromuscular performance measures of strength and leg power in adolescent male and female athletes. Longitudinal increases in knee abduction moments and motion will significantly correlate with the absence of increased leg power in girls. Longitudinal decreases in knee stiffness during landing would significantly correlate with the absence of increased hamstrings strength in girls.

A summary of the dissertation results with additional discussion and conclusions are presented in Chapter 6. In addition, practical implications related to female ACL injury prevention are presented.

Delimitations

This study was delimited to male and female athletes within the Boone County, Kentucky School District. The athletes that were included in this study were soccer and basketball that participated in school sponsored teams. A total of 315 subjects were included in this study and were tested twice over the span of approximately one year. Subjects were excluded from this study if they had previous history of knee or ankle surgery. Two measures were used to identify the maturational development of each subject. The first measure was the modified Pubertal Maturational Observational Scale (PMOS).[41] The second measure of maturation was an estimate of percent of adult stature.

We delimited the movement analyzed to a drop vertical jump (DVJ). This task was chosen because it has been used effectively to identify differences in female athletes that subsequently suffered an ACL injury compared to athletes that did not.[27] Sex differences have been identified previously with the DVJ, in addition to greater magnitudes of knee abduction compared to single leg maneuvers.[15, 42]

Limitations

The key feature of a longitudinal study is that the same subjects are tested multiple times.[43] Beuenen and Malina[44] reviewed the difficulties and limitations of longitudinally measured physical performance attributes. For example, a testing or learning effect may be observed when the same task is performed over multiple years. A learning effect could result in poor repeatability, as the subject may improve task performance over time. A repeatability study, with a subset sample of subjects, was undertaken to address this potential limitation.[45] Measures of kinematic, kinetic and performance measures were excellent to good between sessions that were seven weeks apart.[45] Specific techniques were systematically used during data collection in an effort to enhance reliability of the collected measures. For example, in the current study, standardized camera and force plate locations were used during repeated measurement sessions. Verification and quality control of calibration procedures were also performed daily during data collection.[46] Marker reapplication has been suggested to contribute to decreased reliability.[47] Data collection via video based motion analysis systems is susceptible to kinematic cross-talk errors.[48] Cross-talk errors result from the primary (flexion) calculations of the embedded axis "bleeding" into the calculations of secondary axes (abduction-adduction, internal-external). Ramakrishnan and Kadaba[49] preformed a sensitivity analysis to estimate errors due to incorrectly defining the embedded axes at the hip and knee. During gait, the sagittal plane measures at the hip and knee were relatively unaffected by analytical displacement of the flexion-extension axes.[49] In contrast, they reported large errors for hip and knee abduction-adduction and internal-external rotations that they attributed to cross-talk.[49] Errors may be reduced by standardized marker placement (single investigator placement) and through standardized reference static alignment (foot placement and posture). One well trained and experienced investigator to place markers on the subjects was used as marker reapplication has been attributed to lower reliability.[47] A reference static alignment (neutral pose) was standardized with consistent foot placement and posture. In addition, standardized instructions and data collection procedures were employed during all testing sessions.

Subject motivation is another factor that could alter the measured results due to variation in the willingness to perform the task.[44] To address the concern of subject motivation, a suspended basketball was positioned at each subject's previously measured maximum vertical jump height. The use of an overhead goal has been shown to increase vertical jump height and to provide standardized extrinsic motivation to encourage maximal effort jumping during the task.[50]

A primary advantage of longitudinal studies is that individual changes can be identified serially.[44] A limitation in our study, however, was that group differences between pubertal groups were cross-sectional in nature, as we did not follow the subjects through pubertal and post-pubertal stages of development. Follow-up studies will be performed that follow individuals in a longitudinal nature throughout adolescent development. Longitudinal study designs are also sensitive to missing data points.[43] We chose to use a repeated measures ANOVA and standard bivariate correlation on serial changes or deltas for the statistical tests that did not allow for the analysis of missing data. Therefore, if data were missing, they were excluded from the analysis. A more robust statistical analysis should be considered to increase the number of subjects with multiple visits. For example, a key feature of mixed effects regression is that missing repeated measurements are handled appropriately (uneven number of repeated measures among subjects).

Assumptions

Several assumptions were made prior to the study. We assumed that the study instruments were valid and reliable in the population tested. Several previous reports have supported this assumption with validity and reliability studies. For example the PMOS scale (Appendix B) has shown high reliability and can be used to differentiate between pubertal stages based on indicators of adolescent growth, breast development, menstruation status, axillary and leg hair growth, muscular development, presence of acne and evidence of sweating during physical activities.[36, 51-53] The motion analysis techniques were also assumed to be reliable in this study. As detailed above, previous reports have supported this claim in similar populations.[45]

Definition of Terms

The following terms used in the study are defined below.

Abduction: Abduction refers to the frontal plane rotation of the distal segment away from midline. For instance, knee abduction would be representative of the tibial segment, in reference to the thigh segment, rotating away from midline. Valgus and abduction are used interchangeably and denotes the same rotation. Negative values in our model represent increasing magnitudes of abduction.

Active joint stiffness (also see stiffness): In the current study we estimate *active joint stiffness* based on the formula of rotational stiffness (k = applied joint moment/angular displacement). This model takes advantage of the moment-angle relationship where angular displacement is regulated by the external moment. Active joint stiffness is specifically calculated as the slope of the moment-angle curve.[54] Knee joint stiffness is used synonymously with active joint stiffness when discussing the knee joint.

Adolescence: Malina & Bouchard (1991) state that adolescence is difficult to classify based on chronological age.[55] However, the definition used in this study for female adolescence is 8 to 19 years and 10 to 22 years in males.[55]

Leg stiffness (also see stiffness): The application of a linear spring model to represent the legs (spring) supporting the body mass. Specifically, leg stiffness (also called vertical stiffness) can be defined as the ratio of the force to the displacement (maximum force/Δ whole body center of mass displacement).[56]

Maturation: Maturation is defined as the process of becoming mature. It describes the time and rate of moving towards a mature biological state.[55]

Neuromuscular control: Neuromuscular control specifically relates to the activation of the dynamic restraints surrounding a joint in response to sensory stimuli.[57]

Peak height velocity: Peak height velocity (PHV) is a commonly used indicator of maturity that represents the time of maximum rate of growth during adolescence. A mathematical or graphical curve fitting technique is often used to estimate age at PHV.

Percent of adult stature: Percent of adult stature is used as a somatic indicator of maturity.[55] In the current study, adult stature was estimated based on the Khamis-

Roche method developed from the Fels Longitudinal Study which collected data on families residing in southwestern Ohio.[58]

Puberty: Puberty is interrelated with adolescent development. Pubertal stages are based on sexual maturity and related to the development of secondary sex characteristics.[55] These secondary sex characteristics are strongly associated with specific hormonal changes evident throughout adolescent growth. We used a non-invasive scale, PMOS, to classify subjects as pubertal or post-pubertal.[52]

Stiffness: Stiffness is the resistance to a mechanical stretch from an applied force.[59] Calculated stiffness, k, is equal to the ratio of applied force to change in length (displacement).

Chapter 2. Background and Methodological Review

Theoretical rationale

A scientifically based approach is highly recommended for the development of a strategy to prevent sports injuries.[60] The sequence of prevention model was described by van Mechelen[60] that systematically organizes specific scientifically based principles that can be used to effectively develop injury prevention programs. The initial steps involve understanding and establishing the extent of the problem based on injury incidence and severity. ACL injuries are a significant and extensive problem in female athletes. Reduction of female injury rates would potentially allow thousands of females annually to continue the health benefits of sports participation based on the growing numbers of athletes who play high risk sports like soccer and basketball.

Injury Mechanism

The next step in the sequence of injury prevention is to establish the injury mechanism and etiology (Figure 2.1). The relative importance of each risk factor is difficult to evaluate for each individual athlete. However, a detailed description of the inciting event (injury mechanism) is suggested in order to identify the appropriate methods for injury prevention and to allow the theoretical development of potential intrinsic and extrinsic risk factors.[60] Most ACL injuries in female sports occur during a non-contact episode, typically during deceleration, lateral pivoting, or landing tasks that are associated with high external knee joint loads.[61, 62]

There is relative consensus in the literature that approximately 70% - 80% of ACL injuries are non-contact in nature.[29, 62, 63] Video analysis techniques have confirmed, that most non-contact ACL injuries occur during a sharp deceleration or landing maneuver with the knee close to extension at initial ground contact.[62] Olsen et al. performed a videographic examination of ACL injury mechanisms in team handball.[61] They found that the ACL injury mechanism in women was a forceful valgus collapse with the knee close to full extension combined with tibial rotation. These analyses demonstrate relatively common mechanisms, including valgus, extended knee and widened stance, however they also highlight the difficulty of determination of the exact mechanism of injury from eye witness account or even slow motion video.[29]

Risk Factors

Risk factors for most sports injuries are classified into internal (intrinsic) and external (extrinsic) to the athlete. Several typical internal risk factors which may play a role in an injury are listed in Figure 2.1. Risk factors such as age, maturation and neuromuscular performance may predispose the athlete to injury. External risk factors could be considered to interact with the athlete and potentially result in the athlete being susceptible to a certain injury. An inciting event, or mechanism, must occur that would be the actual underlying cause of the injury. The multi-factorial relationship between female athlete and ACL injury must be continually developed and tested with systematic and well defined research questions.

This study tested the interaction between internal risk factors that relate to higher risk of ACL injury in females. Intrinsic (internal) variables associated with ACL injury are typically classified into of anatomic, hormonal, neuromuscular and biomechanical.[29, 35] Numerous ACL injury risk factor studies have focused on anatomic or anthropometric measures such as tibial length, thigh length and height.[64, 65] Lower extremity bone length may underlie increased risk of ACL injuries, however, anatomic measures often do not correlate with dynamic injury mechanisms.[66] Anatomic measures are not typically modifiable, which limits the potential impact of injury prevention focused on these variables. However, a mechanistic relationship may exist between changes in anatomy and other modifiable risk factors.

Rapid changes in anatomical variables (height, segment bone length) occur during pubertal maturation. During puberty the tibia and femur grow at a rapid rate in both boys and girls.[67] This growth of the two longest bones in the human body may relate to greater joint torque and force.[36] Increased height leads to a higher center of mass, and potentially decreased muscular control of mass. Growth and development are associated with hormonal, neuromuscular and biomechanical factors that may underlie the differences in ACL injury risk.[36]

Altered movement patterns

The potentially modifiable intrinsic variables of interest in this study are classified as neuromuscular. Specifically, *altered movement patterns* and *inadequate knee stiffness* are two interrelated factors that may increase ACL injury risk. Altered movement patterns can be described by the specific plane which the majority of the deficit occurs. For example, the sex-based disparity observed in ACL injury rates may be strongly influenced by differences in the frontal plane joint motions and moments. The link between frontal plane knee loading and resultant increases in ACL strain is demonstrated by cadaveric, *in vivo* and computer modeling experiments.[28, 68-70] Physiologic dynamic valgus torques on the knee can significantly increase anterior tibial translation and load on the ACL several-fold.[69]

A prospective combined biomechanical-epidemiologic study showed that knee abduction moments (valgus torques) and angles were significant predictors of future ACL injury risk. Knee abduction moments predicted ACL injury risk with 73% sensitivity and 78% specificity.[27] Knee abduction angles were 8 degrees greater in the ACL-injured than the uninjured groups. It is therefore likely that increases in knee abduction moment and motion in the injured group, were significant risk factors that predisposed each athlete to an ACL injury.

Sex differences in knee abduction motion and moment have been investigated in numerous studies during landing maneuvers with three-dimensional analysis techniques.[14, 15, 36, 42, 71-92] Table 2.1 summarizes the results of a systematic review of the literature that measured knee abduction during a landing task. A search of MEDLINE, CINAHL and SportDISCUS was performed with the following search keywords: "knee AND sport AND (abduction OR valgus OR frontal OR coronal) AND (sex OR gender)." The results were limited to studies that examined a landing maneuver (single or double leg), compared knee abduction (valgus) motion or moments between sexes and used three-dimensional analyses. The majority of the studies found an increased knee abduction (valgus) motion or moment in females compared to males. None of the studies, however, used longitudinal techniques to identify when the differences began to diverge between sexes.[14, 15, 36, 42, 71-92]

Inadequate knee stiffness

Additional intrinsic risk factors are likely to modify or influence movement patterns (knee abduction motion and moments). Therefore, if we follow the theoretical sequence of prevention we should examine the cause of an altered movement pattern to further progress towards an effective injury prevention strategy. Figure 2.2 shows a theoretical example of a modifiable intrinsic risk factor that may play a role in altered movement patterns observed in female athletes that are predisposed to injury. The primary joint stabilizers of the knee are the flexor and extensor muscles and are utilized during dynamic loading conditions to protect against an injury.[93] Active joint stiffness can be voluntarily controlled through muscular recruitment. The co-contraction of the flexor (hamstrings) and extensors (quadriceps) may protect the knee against altered movement patterns (knee abduction). Strength and activation deficits of the hamstrings may limit the potential for muscular co-contraction for the protection of knee ligaments. Similar mechanisms apply to muscular protection against torsional loading, in which sex differences have been identified.[94] Wojtys et al. demonstrated that maximal rotations of the tibia were greater in women than in men in both the passive and the active muscle state.[94] Females exhibited less muscular protection of the knee ligaments under internal rotation loading than did males.[94]

The abilities to decelerate from a landing and to control knee abduction motion and moments could be related to a decreased imbalance in the hamstrings to quadriceps strength and recruitment that was observed in the females prior to neuromuscular training.[11] Co-contraction of the knee flexors is required to balance active contraction of the quadriceps to compress the joint and to assist in the control of high knee abduction torques and anterior tibial translation. Female athletes with decreased ability to adequately balance muscular recruitment through positions of high joint loading may be predisposed to increased risk of ACL injury.

Motor control strategies that rely on feedback loops (reactive) alter muscle activation in response to situations that load the lower extremity joints.[95] The electromechanical time delays that are inherent in feedback mechanisms likely limit the effectiveness of muscular joint protection during dynamic movements.[57] Preparatory muscle activity, however, can stiffen joints prior to unexpected perturbations and can be learned and adjusted through integration of previous movement experiences or training.[95-98] Athletes can adopt or "pre-program" safer movement patterns that may reduce injury risk during landing or pivoting or unexpected loads or perturbations during sports movements. See Appendix A for a review of the associations between co-contraction and age.

Effects of Maturation

Though there likely are multiple factors underlying the differences in ACL injury rates in male and female athletes, neuromuscular control may be the greatest contributor to injury risk and the most modifiable factor. While the focus should remain in areas that are modifiable, where effective interventions can be developed, investigations should continue into the relative contribution of less modifiable factors. This is especially important in the pubescent athlete, where significant developmental changes occur both anatomically and hormonally. The musculoskeletal changes that can alter both passive joint laxity and decrease dynamic joint stability in high-risk female athlete, and potentially lead to higher injury rates in this population, could be modified if interventions were instituted in the right time.

There is no evidence for a sex difference in ACL injury rates in pre-pubescent athletes, which is in direct contrast to injury rates in adolescent and adult populations.[30, 31, 99] Although ACL injuries increase with age in both males and females, females have higher rates immediately following the growth spurt.[100] Insurance data shows that girls and boys separate in knee and ACL injury risk within the same time frame, after girls begin to mature (age 11 to 13).[101] During, and immediately following the growth spurt, body mass and additional risk factors appear to increase in females. These risk factors with the cumulative effects of athletic exposures to injury likely lead to a higher probability of injury in mature females compared to pubertal females. Data from the American Academy of Orthopaedic Surgeons supports this with a peak in the prevalence of ACL reconstructive surgeries in girls at age 16.[102] Therefore, if appears that girls may develop altered movement patterns and inadequate muscle stiffness during this stage of development.

Males demonstrate power, strength and coordination increases with chronological age that correlate to maturational stage, while females show little average change throughout puberty.[44, 103] Correlations between height, weight and neuromuscular performance observed in males are absent in pubescent females. For example, vertical jump height (a measure of whole-body power) increases steadily in males during puberty, but not in females.[103, 104] Musculoskeletal growth during puberty, in the absence of corresponding neuromuscular adaptation, may facilitate the development of certain intrinsic risk factors.[36] These intrinsic risk factors, if not addressed at the proper time, may continue through adolescence into maturity and predispose athletes to ACL injuries. The differences in neuromuscular performance between the sexes during and following puberty may be important contributors to forces on the knee and altered biomechanics that could potentially explain the increased risk of ACL injury in females following puberty and may help identify the optimal time to implement injury prevention programs.[105]

Preventive Measures

Neuromuscular training in females has been shown to increase active knee stabilization in the laboratory and decrease the incidence of ACL injury on the field and court of play in athletic female populations.[7, 11, 23, 66] Neuromuscular training facilitates neuromuscular adaptations that focus on joint stabilization and safe movement patterns. This training allows female athletes to adopt muscular recruitment strategies that decrease joint motion and protect the ACL from the high impulse loading.[66, 106, 107] However, a clearer identification of the putative modifiable mechanisms would increase the potential for both screening for high risk athletes and for targeting interventions to address the specific mechanisms that increase ACL injury risk in female athletes.

Methodological review

Motion Analysis Techniques

Multidisciplinary approaches are typically used to define the potential mechanisms that underlie increased injury risk of musculoskeletal injury and to identify specific factors predictive of injury risk in sports. Specifically, motion analysis techniques have been used to identify potential risk factors for knee injuries.[15, 82, 108-110] However, a majority of these investigations are limited to cross-sectional comparisons between groups (i.e. males versus females). Though cross-sectional comparisons may be important to the overall understanding of the potential biomechanical patterns that may be related to increased injury risk for subsets of athletes, the biomechanical findings are not typically coupled with repeated, longitudinal measures. However, a key component to the utilization of motion analysis techniques to define these problems, especially with longitudinal study designs, is the ability to reliably measure biomechanical variables in individuals both within and between testing sessions.

Reliability

Kadaba et al.[47] conducted one of the first studies to investigate the reliability of quantitative motion analysis techniques. They examined kinematic and kinetic data during normal gait and found that most often the data was more reliable within session than between different testing sessions. Error in reapplication of reflective markers was cited as a potential factor for the lower reliability measures especially in the frontal and transverse planes. [47] Both Ferber et al.[111] and Queen et al.[112] found similar trends of improved within session reliability compared to between testing days during 3D motion analysis of running. These authors also cited marker placement as the most likely cause of decreased between session reliability. In addition, increased reliability has previously been found when comparing sagittal versus frontal and transverse motions.[47, 111-113] Typical out of plane rotations (frontal and transverse) may be more sensitive to reapplication of markers.[49, 111] However, frontal and transverse plane variables may provide essential information during maneuvers that may relate to an injury.[15, 27, 29, 82, 108] Reliability of biomechanical variables specifically during landing maneuvers is not as well defined in the literature. The examination of the reliability of these variables is important, since a rapid deceleration, such as occurs during landing from a jump, is frequently identified during ACL injuries.[61]

Studies involving serial measurements of young athletes throughout maturational development are contingent on reliable data acquisition. Quatman and colleagues evaluated young female and male athletes to determine if changes in maturational development status would affect kinetic patterns during a during a drop vertical jump.[51] They evaluated young athletes over a year time span and found that young females do not develop increased lower extremity power with maturation in a fashion similar to males. This indicates that incorporating additional motion analysis techniques in longitudinal evaluation of young athletes may be warranted if the measures are demonstrated to be reliable over time.

A recent study was performed to determine the reliability of 3D lower extremity kinematic and kinetic variables during landing in young athletes.[45] Eleven athletes were identified who participated in two testing session 7 weeks apart because they played on both the soccer and basketball teams tested. These eleven subjects were used in the reliability study to determine the within and between session reliability of lower extremity biomechanical variables (3 female, 8 male; height:1.64 ± 0.10 m to 1.64 ± 0.10 m, Typical Error = 0.006 m; mass: 53.4 ± 13.0 kg to 54.5 ± 13.2 kg, Typical Error = 0.8 kg; 6.7 ± 1.4 weeks between sessions). Kinematic and kinetic data were normalized to 100% of the stance phase (between IC and TO). The following variables were calculated during the stance phase for each trial: maximum VGRF, maximum joint moment and maximum and minimum joint angle for the hip, knee and ankle. These variables were chosen based on their frequent use in relation to possible injury risk and sex comparison studies.[15, 27, 82, 108, 109] Coefficients of multiple correlations (CMC)[47], intraclass correlation coefficients (ICC(3,k), ICC(3,1))[114] and typical error (TE)[115] (standard deviation of the individual's repeated measures) analyses were used to examine within and between session reliability.

Ford et al.[45] found no differences in within session reliability for peak angular rotations between planes with all variables combined (sagittal ICC ≥ 0.933, frontal ICC ≥ 0.955, transverse ICC ≥ 0.934) (Figure 2.3). Similarly, the between session reliability of kinematic measures (Figure 2.4) were not different between the three planes of motion, but were lower than the within session ICC's. The within and between session reliability of discrete joint moment variables were excellent for all sagittal (within ICC ≥ 0.925, between ICC ≥ 0.800) and frontal plane moment measures (within ICC ≥ 0.778, between ICC ≥ 0.748). CMC analysis revealed similar averaged within session (CMC = 0.830 ± 0.119) and between session (CMC = 0.823 ± 0.124) waveform comparisons. A table of the results is presented in Table 2.2.

The majority of the kinematic and kinetic variables in young athletes during landing have excellent to good reliability. The ability to reliably quantify lower extremity biomechanical variables of young athletes during dynamic tasks over extended intervals may aid in identifying potential mechanisms related to injury risk factors.

Knee stiffness

Muscular co-contraction has been examined experimentally through joint moment analyses, electromyography, model-based estimation of muscle forces, and leg and joint stiffness calculations. Calculation of joint moments through inverse dynamics incorporates the *net* forces which act about the joint.[116] One limitation of net joint moment analysis is that it does not indicate which muscles are active or the individual muscle forces generated at any specific point in time. Therefore, cautious interpretation of the relationship between the joint moment and the actual muscle forces generated is necessary.

Electromyography has been used to calculate a co-contraction index or ratio. However this calculation can be complex and vary significantly among studies. Typically, surface EMG is utilized to obtain agonist and antagonist muscular activation patterns. The EMG signal is the electrical representation of neuromuscular activation focused at the neuromuscular endplate related to a contracting muscle.[117] See Appendix A for a detailed systematic review focused on EMG co-contraction measures.

Other techniques estimate individual muscle forces through computational models. The agonist and antagonist muscle groups can then be further investigated to address co-contraction during different movements. These computer models represent varying degrees of complexity and require detailed information regarding the muscle and skeletal systems.[118]

Stiffness calculations involve the resistance to a mechanical stretch from an applied force.[59] Muscle stiffness is a necessary component of joint stability and may relate to musculoskeletal injury potential.[59] Padua et al.[59] found that females had lower leg stiffness values, in addition to higher quadriceps to hamstrings co-contraction, compared to males. Active joint stiffness is likely increased with hamstrings co-contraction which has been shown to be protective of the ACL. This study focused on joint stiffness calculations as described below. Electromyography was not included in the initial data collection session and therefore could not be used in the analyses of the longitudinal data which was previously collected.

Leg stiffness takes into account the entire lower extremity and has been estimated during jogging, sprinting, jumping, landing and hopping.[54, 56, 59, 119, 120] Typically leg stiffness is calculated based on a simple spring-mass model.[56, 119] Specifically, leg stiffness can be defined as the ratio of the force to the displacement (maximum force/Δ whole body center of mass displacement).[56] Active joint stiffness is a related measure, however, it utilizes a rotational spring model (k = applied joint moment/angular displacement). This model takes advantage of the moment-angle relationship where angular displacement is regulated by the external moment. The stiffness calculation is based on the slope of the moment-angle curve.[54] Figure 2.5 shows a typical stiffness plot comparing male and female subjects. Males had significantly greater knee joint stiffness compared to females during a single leg landing.[37]

Maturational Assessment

Maturation was operationally defined as the process of becoming mature.[55] This definition, however, varies depending on which biological system is being described. Three common indicators of maturation are based on sexual, skeletal and somatic maturity. Sexual maturity is related to the development of secondary sex characteristics.[55]

These secondary sex characteristics are strongly associated with specific hormonal changes evident throughout adolescent growth. While the gold standard rating of secondary sex characteristics is typically performed based on a five-stage scale (criteria described by Tanner), these overlap and have been described as arbitrary.[55] The ratings are typically performed by a physician through direct observation of the genitalia. This invasive method is often an area of privacy concerns among adolescents and adults alike. Non-invasive measures have been developed and compared to the traditional Tanner-stages of sexual maturation. The modified Pubertal Maturational Observational Scale (PMOS) uses both parental questionnaires and investigator observations to classify subjects into the pubertal categories.[52] The PMOS scale (Table B.1) has shown high intersession reliability and can be used to differentiate between pubertal stages based on indicators of adolescent growth, breast development, menstruation status, axillary and leg hair growth, muscular development, presence of acne and evidence of sweating during physical activities.[36, 51-53]

Skeletal age assessments are typically considered one of the best means to estimate maturity status.[55] However, invasive radiographic techniques are typically necessary to evaluate the developing skeleton during adolescent growth. Based on the method used, a skeletal age is calculated which is then related to chronological age.

A somatic maturational assessment utilizes body measurements and often requires longitudinal measurements within each subject. Somatic maturational assessment is traditionally the best way to identify rapid adolescent growth.[55] Anthropometric measurements, typically of stature, are used in several different techniques to estimate final adult stature or the age at peak height velocity (PHV). When annual, longitudinally measured height is collected, the percentage of adult stature can be calculated from the final height. This is a useful indicator of somatic maturity and can be used to normalize a comparison group based on maturation. PHV is another useful indicator of maturity which is used mostly to identify the timing of growth. A mathematical or graphical curve fitting technique is typically used to estimate age at PHV. However, regression techniques have been developed to estimate both PHV and percentage of adult height based on additional measurements.[58] The Khamis-Roche method of estimated adult stature was developed from the Fels Longitudinal Study that collected data on families residing in southwestern Ohio.[58] The use of the subject's stature, mass, midparental stature and age was utilized to develop regression equations for boys and girls (Appendix C, Table C.1, Table C.2). This method was found to be comparable to estimates which included invasive measures of skeletal age.[58]

Summary

ACL injury risk factors may relate to altered movement patterns and inadequate knee stiffness.[35] Experimental techniques were described that could be used to measure knee abduction motion, knee abduction moment and active joint stiffness in a large cohort of young athletes. The novel combination of detailed biomechanical analyses with maturational classifications was used in this longitudinal study. The three subsequent chapters detail the results and specifically identify the connection to increased ACL injury risk in mature females.

Table 2.1. Summary of studies focused on sex differences in 3D calculated knee abduction

First Author (Year)	Subjects	Ages	Tasks	Instrumentation	Variables	Results
Benjaminse (2008)[71]	Recreational athletes		Single leg stop jump	3D passive motion 6 cameras	Knee abduction angle	No sex difference
	Males (n = 15)	22.7 ± 1.6				
	Females (n = 15)	22.1 ± 1.7				
Chappell (2007)[72]	Recreational athletes		Double leg vertical stop jump	3D passive motion 8 cameras	Knee abduction angle flight phase	No sex difference
	Males (n = 17)	22.6 ± 2.2				
	Females (n = 19)	22.3 ± 2.2				
Chappell (2002)[14]	Recreational athletes		Double leg forward jump Double leg vertical stop jump Double leg backward jump	3D passive motion 4 cameras 2 force platforms	Knee abduction moment during landing	Females increased abduction
	Males (n = 10)	23.4 ± 1.1				
	Females (n = 10)	21.0 ± 1.7				
Chaudhari (2007)[73]	Recreational athletes		Single leg horizontal hop Double leg box drop vertical Double leg vertical jump	3D passive motion 2 cameras 1 force plate	Knee abduction moment	No sex difference
	Males (n = 12)	20.3 ± 1.7				
	Female – no oral contraceptive (n = 12)	19.1 ± 1.0				
	Female - oral contraceptive (n = 13)	20.3 ± 1.0				
Cortes (2007)[74]	University students (exercise 30min/day at least 3 times/week)		Double leg box drop vertical	Electromagnetic sensors 2 force platforms	Knee abduction angle	No sex difference
	Males (n = 25)	24.4 ± 2.3				
	Females (n = 25)	23.3 ± 2.5				

Table 2.1 (cont.)

First Author (Year)	Subjects	Ages	Tasks	Instrumentation	Variables	Results
Earl (2007)[42]	Moderately active (exercise 30min/day at least 3 times/week)		Double leg box drop vertical Single leg step down	3D passive motion 6 cameras	Knee abduction angle	Females increased abduction
	Males (n = 18)	23.5 ± 3.8				
	Females (n = 19)	22.2 ± 2.6				
Ford (2003)[15]	High school basketball players		Double leg box drop vertical	3D passive motion 8 cameras 2 force platforms	Knee abduction angle	Females increased abduction
	Males (n = 34)	16.0 ± 1.2				
	Females (n = 47)	16.0 ± 1.4				
Ford (2006)[75]	College athletes (Division I)		Single leg medial box drop Single leg lateral box drop	3D passive motion 8 cameras 2 force platforms	Knee abduction angle	Females increased abduction at IC Females increased abduction peak
	Males (n = 11)					
	Females (n = 11)					
Garrison (2005)[76]	College soccer players		Single leg box drop	3D passive motion 10 cameras 1 force platform	Knee adduction moment Knee abduction moment	Females decreased adduction No sex difference
	Males (n = 8)	19.3 ± 1.5				
	Females (n = 8)	22.1 ± 2.4				
Gehring (2009)[77]	Physically active		Double leg box drop landing	3D passive motion 6 cameras 1 force platform	Knee abduction angle	Females increased abduction
	Males (n = 13)	25.0 ± 2.4				
	Females (n = 13)	22.6 ± 1.5				
Hart (2008)[78]	College soccer (Division I)		Single leg forward hop	3D passive motion 10 cameras 1 force platform	Knee abduction angle Knee abduction moment	Males decreased adduction angle No sex difference
	Males (n = 8)	19.1 ± 1.4				
	Females (n = 8)	22.0 ± 2.1				

Table 2.1 (cont.)

First Author (Year)	Subjects	Ages	Tasks	Instrumentation	Variables	Results
Hewett (2004)[36]	Soccer and basketball players		Double leg box drop vertical	3D passive motion 8 cameras 2 force platforms	Knee abduction angle	Post pubertal females increased abduction compared to post pubertal males Post pubertal females increased abduction compared to prepubertal and pubertal females
	Male - prepubertal (n = 27)	12.0 ± 0.6				
	Male - pubertal (n = 24)	14.2 ± 1.4				
	Male - post pubertal (n = 30)	15.8 ± 1.7				
	Female - prepubertal (n = 14)	11.5 ± 0.7				
	Female - pubertal (n = 28)	12.6 ± 1.1				
	Female - post pubertal (n = 58)	15.5 ± 1.5				
Hughes (2008)[79]	University volleyball players		Double leg volleyball block landing	3D passive motion 12 cameras 2 force platforms	Knee abduction angle	Females increased abduction
	Males (n = 6)	21.6 ± 3.3				
	Females (n = 6)	21.2 ± 1.3				
Jacobs (2005)[80]	Recreational athletes		Single leg forward hop	3D passive motion 6 cameras	Knee abduction angle	No sex difference
	Males (n = 8)	24.1 ± 2.2				
	Females (n = 10)	22.1 ± 2.3				
Jacobs (2007)[81]	Healthy adults		Single leg forward hop	Electromagnetic sensors	Knee abduction angle	No sex difference
	Males (n = 15)	24.4 ± 3.0				
	Females (n = 15)	23.2 ± 2.9				

Table 2.1 (cont.)

First Author (Year)	Subjects	Ages	Tasks	Instrumentation	Variables	Results
Kernozek (2005)[82]	Recreational athletes Males (n = 15) Females (n = 15)	 24.5 ± 2.3 23.6 ± 1.8	Double leg drop landing	3D passive motion 6 cameras 1 force platform	Knee abduction angle Knee abduction moment	Females increased abduction Females decreased abduction moment
Kernozek (2008)[83]	Recreational athletes Males (n = 16) Females (n = 14)	 23.8 ± 0.4 23.0 ± 0.9	Double leg drop landing	3D passive motion 6 cameras 1 force platform	Knee abduction angle Knee abduction moment	Females increased abduction angle No sex difference in moment
Kiriyama (2009)[84]	Healthy high school students Males (n = 88) Females (n = 81)	 17.1 ± 0.8 16.9 ± 1.2	Single leg box drop	3D optoelectronic tracking system 1 force platform	Knee abduction angle	No sex difference
McLean (2007)[85]	College athletes (Division I) Males (n = 10) Females (n = 10)	 20.7 ± 1.3 20.8 ± 0.8	Double leg box drop vertical	3D passive motion 6 cameras 2 force platforms	Knee abduction angle Knee abduction moment	Females increased abduction angle Females increased abduction moment
Nagano (2007)[86]	University athletes Males (n = 18) Females (n = 19)	 19.8 ± 4.6 19.4 ± 0.9	Single leg box drop	3D passive motion 7 cameras 1 force platform	Knee abduction angle	No sex difference
Pappas (2007)[87]	Recreational athletes Males (n = 16) Females (n = 16)	 28.8 ± 3.9 28.2 ± 5.4	Double leg box drop Single leg box drop	3D passive motion 8 cameras 1 force platform	Knee abduction angle	Females increased abduction angle
Pappas (2007)[88]	Recreational athletes Males (n = 16) Females (n = 16)	 28.8 ± 3.9 28.2 ± 5.4	Double leg box drop	3D passive motion 8 cameras 1 force platform	Knee abduction angle	Females increased abduction angle

Table 2.1 (cont.)

First Author (Year)	Subjects	Ages	Tasks	Instrumentation	Variables	Results
Russell (2006)[89]	Healthy subjects		Double leg drop landing	3D passive motion 10 cameras 1 force platform	Knee abduction angle	Females increased abduction angle
	Males (n = 16)	24 ± 5				
	Females (n = 16)	21 ± 6				
Swartz (2005)[90]	Recreational athletes		Double leg landing (50% effort vertical jump)	3D passive motion 6 cameras 1 force platform	Knee abduction angle	No sex difference Children increased abduction angle compared to adults
	Males - adults (n = 14)	23.6 ± 3.2				
	Males - children (n = 15)	9.6 ± 1.0				
	Females - adults (n = 14)	24.2± 2.3				
	Females - children (n = 15)	9.2 ± 1.0				
Wallace (2008)[91]	Female athletes (Division III), Male athletes (recretional)		Double leg drop vertical	3D passive motion 6 cameras 1 force platform	Knee abduction angle	No sex difference
	Males (n = 11)	24.1 ± 3.4				
	Females (n = 11)	19.0 ± 0.9				
Yu (2005)[92]	Youth recreational soccer players		Double leg vertical stop jump	3D passive motion 6 cameras 2 force platforms	Knee abduction angle	Females increased abduction angle Females increased abduction motion as they got older
	Males (n = 30)	5 per age group 11 - 16				
	Females (n = 30)	5 per age group 11 - 16				

Table 2.2. Within and between session reliability measures of both discrete and waveform data.

Variable		**Within Session**			**Between Session**	
Joint Angles (deg)	**CMC**[a]	**ICC(3,k)**[b]	**TE**[c]	**CMC**[a]	**ICC(3,1)**[b]	**TE**[c]
Hip Flexion	0.971	0.956	2.9	0.950	0.595	5.5
Hip Adduction	0.712	0.955	1.6	0.689	0.791	2.0
Hip Internal Rotation	0.721	0.934	2.9	0.652	0.699	3.0
Knee Flexion	0.989	0.933	3.2	0.982	0.616	4.2
Knee Abduction	0.799	0.993	0.9	0.650	0.855	2.3
Knee Internal Rotation	0.696	0.971	1.4	0.706	0.872	1.9
Ankle Dorsiflexion	0.986	0.955	1.6	0.991	0.922	1.3
Ankle Eversion	0.881	0.966	1.9	0.806	0.835	2.3
Joint Moments (Nm/kg)						
Hip Flexion	0.927	0.904	0.23	0.942	0.800	0.19
Hip Abduction	0.710	0.778	0.14	0.739	0.766	0.08
Hip Internal Rotation	0.824	0.882	0.10	0.828	0.655	0.10
Knee Flexion	0.954	0.926	0.15	0.957	0.843	0.13
Knee Abduction	0.692	0.931	0.12	0.711	0.870	0.10
Knee Internal Rotation	0.654	0.666	0.08	0.766	0.592	0.05
Ankle Dorsiflexion	0.908	0.925	0.12	0.939	0.825	0.19
Ankle Eversion	0.848	0.779	0.10	0.864	0.748	0.06

[a] Coefficient of multiple correlation (CMC) comparing within and between session waveform data. [b] Intraclass correlation coefficient (ICC) for the peak measure of each variable. [c] Typical error (TE) in the measurement unit for the peak measure of each variable. [45]

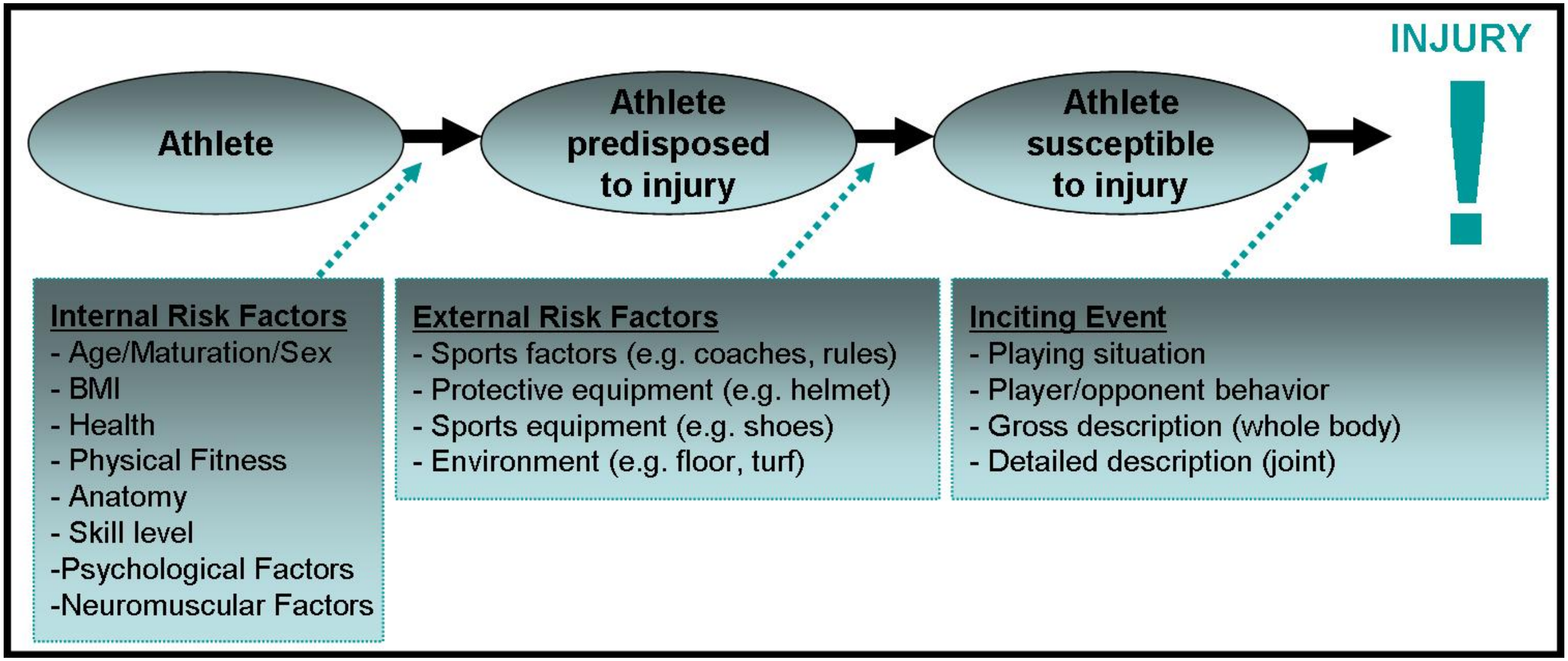


Figure 2.1. Theoretical relationship between athlete, risk factors, inciting event and injury.

Modified from Bahr et al.[121]

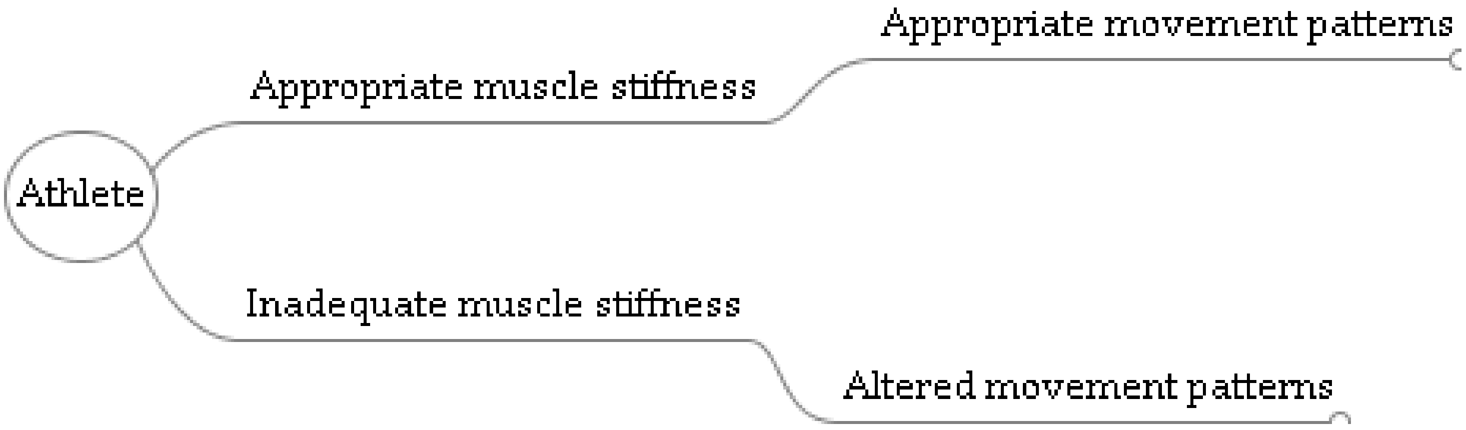


Figure 2.2. Possible role of muscle stiffness.

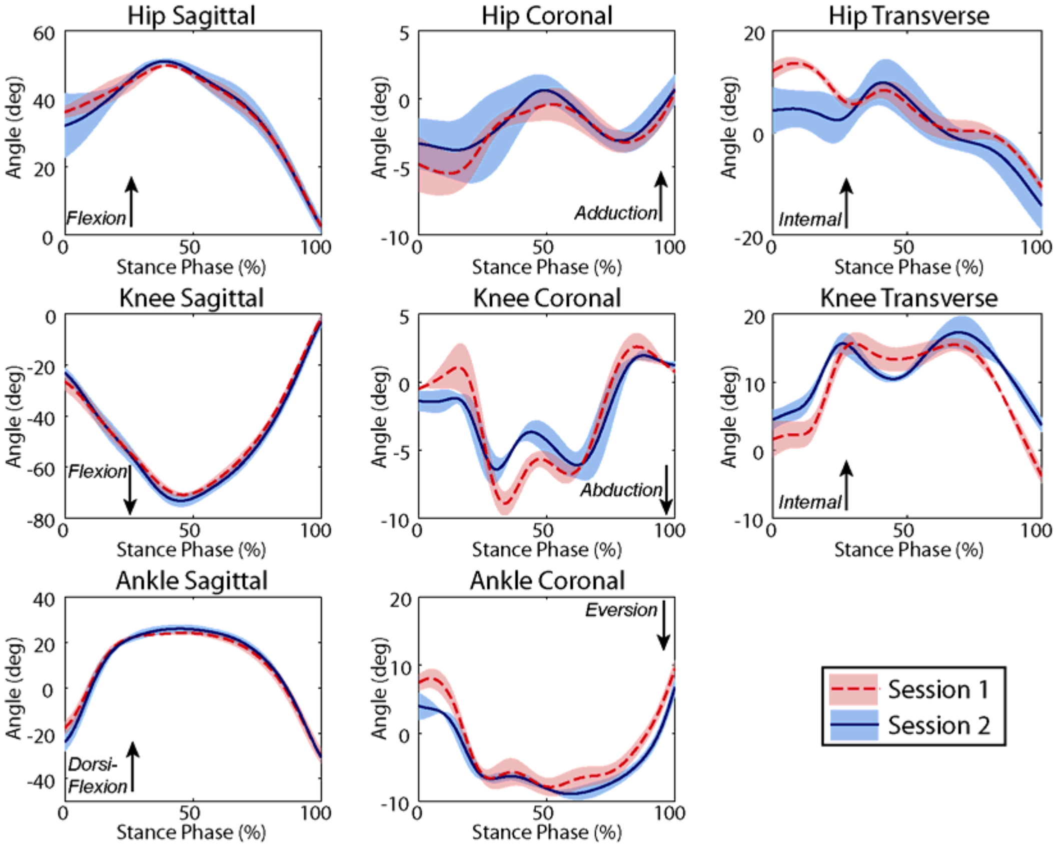


Figure 2.3. Reliability of joint kinematics.

Representative subject (sub5r) kinematic data 7 weeks apart between sessions. Data is the mean (± standard deviation) of three trials.[45]

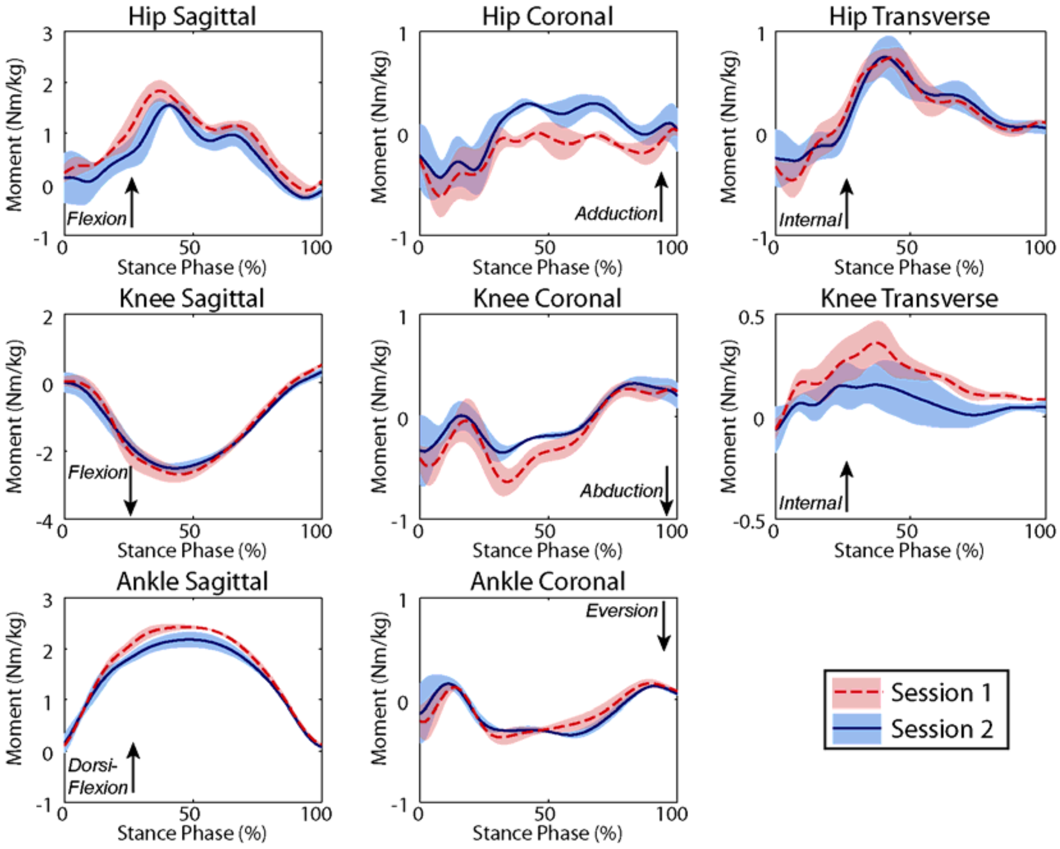


Figure 2.4. Reliability of joint moments.

Representative subject (sub5r) kinetic data 7 weeks apart between sessions. Data is the mean (± standard deviation) of three trials. [45]

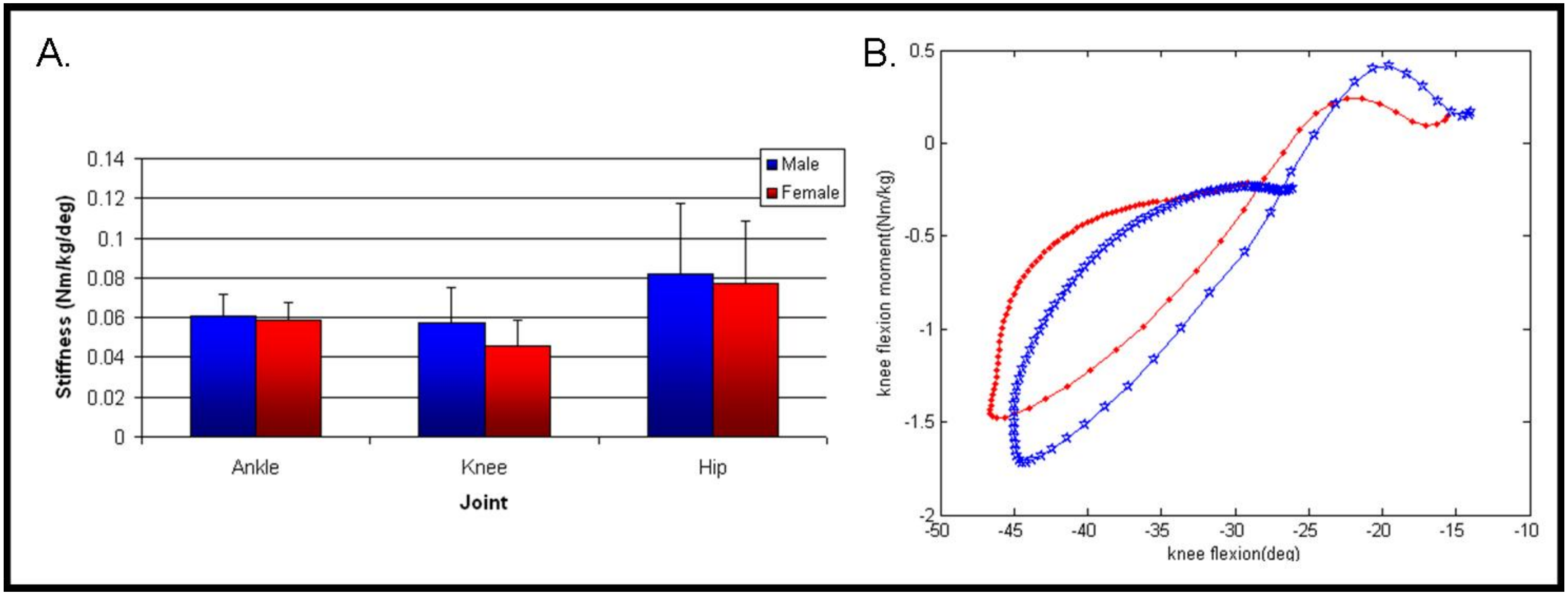


Figure 2.5. Joint stiffness during single leg landing.

A) Mean joint stiffness at the ankle, knee and hip during a single leg landing. Significant sex differences were found in knee stiffness

B) Moment-angle plot during a single leg landing in male (blue) and female (red) athletes.

Chapter 3. Altered Movement Patterns

Introduction

Neuromuscular risk factors may be critical components of the mechanisms underlying the higher rate of ACL injuries in female compared to male athletes. Specifically, altered movement patterns such as knee abduction (valgus) may relate to an increase ACL injury risk. Several studies have shown increased knee abduction motion and load in females compared to males during a variety of landing and pivoting movements.[13-17, 36, 75, 82, 87, 122, 123] Similar lower extremity abduction posture has been reported in females at the time of injury.[61, 62, 124] In addition, a prospective combined biomechanical-epidemiologic study showed that knee abduction moments (valgus torques) and angles were significant predictors of future ACL injury risk. Knee abduction moments predicted ACL injury risk with 73% sensitivity and 78% specificity.[27] Knee abduction angles were 8 degrees greater in the ACL-injured than the uninjured groups. It is therefore likely that the increases in knee abduction moment and motion in the injured group were a significant risk factor that may have predisposed these athletes to an ACL injury.

The onset of these neuromuscular risk factors may coincide with rapid adolescent growth that results in the divergence of a multitude of neuromuscular parameters between sexes. Following an adolescent growth spurt, increased body mass and height of the center of mass may lead to altered movement patterns.[36] Therefore, the timing of adolescent growth may be the critical phase of growth and development related to sex differences in ACL injury risk. However, at this time the effect of rapid growth and development in females on ACL risk factors is unknown.

The purpose of this study was to determine if the specific timed onset of neuromuscular risk factors related to abnormal movement patterns increase in females, but not males, during the adolescent growth spurt. I hypothesized that during adolescent growth, pubertal females would have longitudinal increases in knee abduction moments and motion compared to pubertal males. I also hypothesized that following the adolescent growth spurt, post-pubertal females would have significantly greater knee abduction moments and motion compared to post-pubertal males.

Methods

Subjects

A nested cohort design (total sample female n = 709; total sample male n = 250) was used to select a subset of 315 subjects that were included in this study and classified into two separate maturational groups. The maturational status, either pubertal (n = 182) or post-pubertal (n = 133), was based on the modified Pubertal Maturational Observational Scale (PMOS).[41] If the subject met the pubertal criteria during the first or second year of testing they were operationally defined as pubertal in order to include all subjects that were close to this maturational stage. Subjects classified as post-pubertal had to meet the post-pubertal criteria on the first year of testing. The PMOS incorporates both parental questionnaires and investigator observations to classify subjects into the pubertal categories.[52] The PMOS scale (Appendix B) has shown high reliability and can be used to differentiate between pubertal stages based on indicators of adolescent growth, breast development, menstruation status, axillary and leg hair growth, muscular development, presence of acne and evidence of sweating during physical activities.[36, 51-53]

Detailed demographics of both the male and female subjects are included in Table 3.1. Each subject participated in the first testing session immediately prior to their basketball or soccer season. Approximately one year after the initial testing session (mean 365.7 ± 14.7 days) the subjects were retested using the same methods. Subjects were excluded from this study if they had previous history of knee or ankle surgery. The estimated percent of adult stature of pubertal subjects (female year 1: 87.8 ± 3.4%, female year 2: 91.8 ± 2.7%; male year 1: 87.7 ± 4.5%, male year 2: 91.7 ± 3.9%) and post-pubertal subjects (female year 1: 94.7 ± 3.4%, female year 2: 96.9 ± 3.0%; male year 1: 96.7 ± 2.3%, male year 2: 98.4 ± 1.5%) was similar ($p = 0.3$) between sexes. Regression equations used to estimate adult stature are for female and males are presented in Appendix C.[58]

The data collection procedures were approved by Cincinnati Children's Hospital Institutional Review Board. Each parent or guardian reviewed and signed the Institutional Review Board approved consent to participate form prior to data collection. Child assent was also obtained from each subject prior to study participation. The database review and data analysis was certified exempt (Protocol No. 08-0928-X4B) under the University of Kentucky's Institutional Review Board based on federal regulation 45 CFR 46.101(b) for the protection of human subjects related to the study of existing data.

Procedures

Height was measured with a stadiometer with the subject in bare feet. Mass was measured on a calibrated physician scale. Each subject was then instrumented with 37 retroreflective markers placed bilaterally on the shoulder, elbow, wrist, ASIS, greater trochanter, thigh, medial and lateral knee, tibial tubercle, shank, distal shank, medial and lateral ankle, heel, dorsal surface of the midfoot, lateral foot (5th metarsal) and toe (between 2nd and 3rd metatarsals) in addition to the sacrum, left PSIS and sternum (Figure 3.1). A static trial was first collected in which the subject was instructed to stand still in the anatomical position with foot placement standardized. This static measurement was used as each subject's neutral (zero) alignment. Each subject performed three trials of the drop vertical jump (DVJ). The DVJ consisted of the subject starting on top of a 31 cm box with their feet positioned 35 cm apart. They were instructed to drop directly down off the box and immediately perform a maximum vertical jump, raising both arms as if they were jumping for a basketball rebound.[15]

Trials were collected with EVaRT (Version 4, Motion Analysis Corporation, Santa Rosa, CA) using a motion analysis system consisting of eight digital cameras (Eagle cameras, Motion Analysis Corporation, Santa Rosa, CA) positioned in the laboratory and sampled at 240 Hz. Prior to data collection the motion analysis system was calibrated with a two-step process, first using a static calibration frame to orient the cameras with respect to the laboratory coordinate system and second using dynamic wand data to fine tune camera positions, calculate the lens distortion maps and calculate the lens focal length. Two force platforms (AMTI, Watertown, MA) were sampled at 1200 Hz and time synchronized with the motion analysis system. The force platforms were embedded into the floor and positioned 8 cm apart so that each foot would contact a different platform during the stance phase of the DVJ.

Data Analysis

Following data collection, 3D marker trajectories were examined for accurate marker identification within EVaRT (Version 4, Motion Analysis Corporation, Santa Rosa, CA) and exported to a C3D formatted file. The C3D files were then further analyzed in Visual3d (Version 4.0, C-Motion, Inc., Germantown, MD). The procedures within Visual3D first consisted of the development of a static model customized for each subject. The model's coordinate system convention was +X towards the subject's right (medial-lateral), +Y forward (posterior-anterior) and +Z up (distal-proximal).

The pelvis, thigh, shank and foot segments were generated based on reflective markers from the static trial. Pelvis proximal joint center was assumed to be located at 50% of the distance between left and right ASIS markers (mid-ASIS) (X direction) and 50% of the distance from marker on the sacrum to the mid-ASIS (Y direction). The sacrum, right ASIS and left ASIS markers were used as tracking markers for the pelvis segment (Figure 3.1). The hip joint center was aligned in the anterior direction (Y) with greater trochanter marker. The hip joint center in the Y direction was positioned medially from the ASIS 14% of the inter-ASIS distance.[125] In the Z direction, the hip joint center was located distally from the ASIS 30% of the inter-ASIS distance.[125] Tracking markers for the thigh segment were placed on the greater trochanter, middle of the thigh and lateral knee (Figure 3.1). The knee and ankle joint centers were positioned 50% of the distance between the medial and lateral knee and ankle markers, respectively. Markers placed on the tibial tubercle and middle and distal portions of the shank were used as tracking markers for the shank. The foot segment tracking markers were the heel, instep, lateral foot and toe (Figure 3.1).

Segment lengths were estimated as the distance between the proximal and distal joint center (e.g. thigh segment distance was equal to the distance between the hip joint center to knee joint center). The subjects were positioned for the static trial in a standardized position in order to align the global coordinate system with each segment coordinate system. The pelvis coordinate system was considered aligned with the global lab. The Z axis for thigh segment coordinate system was calculated as the unit vector from the hip to knee joint center. The Y axis was then defined as the unit vector perpendicular to the Z axis and the anatomical plane formed based on the hip and knee joint centers and lab projected lateral hip marker. The X axis was orthogonal to the Y and Z axes based on the right hand rule. The local shank segment coordinate system Z axis was the unit vector from the knee to ankle joint center. The unit vector perpendicular to the shank Z axis and frontal plane (knee and ankle joint centers and lab projected lateral knee marker) formed the shank Y axis. The shank X axis was then defined orthogonal to the Y and Z axes. The foot local Y axis was calculated as the unit vector from the ankle joint center to the toe. The local Z axis was then defined as perpendicular to the Y axis and plane formed based on projected lateral ankle marker and toe and ankle center. The mass and inertial properties for each segment were based on sex-specific parameters from de Leva.[126] and listed in detail in Table 3.2. The subject's height and mass were included in each model.

Custom MATLAB code (Appendix D) was used to batch process each subject through the Visual3D pipeline. The code generated a text file that the Visual3D pipeline engine could read and process the subject-specific model and kinematic and kinetic analyses. 3D marker trajectories from each trial were filtered at a cutoff frequency of 12 Hz (low-pass fourth order Butterworth filter) determined based on residual analysis techniques (see Appendix D).[116] 3D knee joint angles were calculated according to the cardan rotation sequence (i.e. flexion/extension, abduction-adduction and internal-external rotation).[127] Kinematic data were combined with force data to calculate knee joint moments using inverse dynamics.[128, 129] The ground reaction force was filtered through a low-pass fourth order Butterworth filter at a cutoff frequency of 12 Hz in order to minimize possible impact peak errors.[130, 131] Net external knee moments are described in this paper and represent the external load on the joint. Knee abduction angle and knee external abduction moment are represented as negative values based on the analysis convention. The kinematic and kinetic data were exported to MATLAB (mat file) and the peak knee abduction angle and moment (negative) were calculated during the deceleration phase of the initial stance phase of the DVJ. The deceleration phase was operationally defined as being from initial contact (VGRF first exceeded 10 N) to the lowest vertical position of the body center of mass (Figure 3.2). The right side data were used for statistical analysis.

Statistical Analysis

Two between group independent variables of sex (female, male) and maturation level (pubertal, post-pubertal) in addition to the within subject independent variable (repeated measure) of two consecutive year screening sessions were used in the statistical design. The dependent variables were peak knee abduction angle and moment. A 2X2X2 ANOVA (maturation, sex, session) was used to test each hypothesis. Post-hoc analyses was used if significant interactions were observed between factors. An $\alpha \leq 0.05$ was used to indicate statistical significance. Analyses were conducted using SPSS v16.0 (SPSS Inc., Chicago, IL).

Results

Knee Abduction Angle

Mean knee abduction angle during the DVJ stance phase is presented in Figure 3.3. There was a significant three-way interaction with peak knee abduction angle ($p = 0.029$). Post hoc analysis, focusing on the pubertal group, identified a significant longitudinal increase in peak abduction angle in females ($p < 0.001$) but no change in males ($p = 0.90$). Figure 3.4 shows the longitudinal increase in knee abduction angle during one year of adolescent growth in pubertal females compared to pubertal males. The mean difference in stature during this year was 4.8 ± 2.4 cm in females and 6.6 ± 2.8 cm in males.

Increased stature in post-pubertal females was 1.0 ± 2.6 cm and 1.6 ± 2.2 cm in males. Within this cohort of post-pubertal athletes, females and males did not show significant longitudinal changes ($p > 0.05$) in peak knee abduction (Figure 3.4). However, females did have significantly greater overall peak abduction angle following adolescent growth compared to males (female -9.3 ± 5.7°; male -3.6 ± 4.6°; $p < 0.001$).

Knee Abduction Moment

Figure 3.5 details the mean knee abduction moment for maturation and sex groups over each year. A three-way interaction was not significant for peak knee abduction moment ($p = 0.07$). There was a significant main effect of year ($p < 0.001$) indicating longitudinal increases in peak knee abduction moment in the subjects overall (Figure 3.6). A two-way interaction between sex and maturation group was identified ($p = 0.013$). Post-hoc analysis indicated that post-pubertal females had significantly greater peak knee abduction moment compared to post-pubertal males (female -21.9 ± 13.5 Nm; male -13.0 ± 12.0 Nm; $p = 0.017$). Sex differences in knee abduction moment were not found in pubertal subjects ($p > 0.05$).

The results remained similar when knee abduction moment was normalized to body mass (three-way interaction $p = 0.093$, main effect of year $p = 0.001$). In addition, a two-way interaction between sex and maturation group was consistent with the un-normalized moment ($p = 0.016$). Post-hoc analysis indicated that post-pubertal females landed with significantly greater body-mass normalized knee abduction moment compared to males (female -0.37 ± 0.23 Nm/kg; male -0.18 ± 0.16 Nm; $p = 0.002$). Sex differences in normalized knee abduction moment were not found in pubertal subjects ($p > 0.05$).

Discussion

The purpose of this investigation was to determine if the timed onset of specific neuromuscular risk factors related to abnormal movement patterns increase in females, but not males, during the adolescent growth spurt. The pubertal group of male and female athletes showed an increase in stature that indicated they were going through rapid adolescent growth compared to the post-pubertal group. Within the pubertal athletes females exhibited an increase in peak knee abduction angle compared to the males. Both male and female athletes had increased knee abduction moments from the first to second testing session. These observed increases may partially be explained by the increased mass that also occurred between the testing sessions in all athletes. The increases in knee abduction, a potentially modifiable risk factor, may coincide with the increased risk of ACL injury in female athletes compared to males.[36] While several studies have demonstrated that females land with greater knee abduction angles, the current study identifies, through longitudinal measures, a possible relationship between maturational group and increase in a proposed ACL injury risk factor. The combination of increased motion and torque in female athletes may predispose them to increased risk of injury as they develop and mature.

Cross-sectional differences in knee abduction angle among maturational groups has been previously shown.[36] Similar to our current study, Hewett et al. found significant differences in knee abduction angle in post pubertal but not pubertal athletes.[36] The post-pubertal females also had significantly greater knee abduction angle than pubertal females.[36] In addition, a recent study showed similar results with maturing females exhibiting greater knee valgus posture during DVJ.[132] Schmitz et al.[132] found in a cross-sectional study that females classified as Tanner Stage 1 or 2 had less knee valgus posture compared to females classified as Tanner Stage 4 or 5. The measure of knee valgus in the Schmitz et al.[132] study incorporated a two-dimensional frontal plane angle calculated from digital video. While this measure may involve additional rotations of the hip, knee and ankle, these authors did find similar results based on maturation within female subjects. In this study, I chose to examine pubertal compared to post-pubertal athletes with the hypothesis that increased knee abduction would be observed during puberty in females, but not in males. Yu et al.[92] investigated the effects of age and gender on lower extremity movement in male and female soccer players between 11 and 16 years as they performed a stop jump task. They found that knee abduction angle was greater in female subjects that were older compared to the younger subjects.[92]

The findings supported the first hypothesis that through longitudinal analyses pubertal female athletes increased peak knee abduction angle during a year of rapid adolescent growth. Knee abduction angle was not changed in post-pubertal females from the first to second year testing session. However, the post-pubertal females exhibited significantly greater knee abduction angle than post-pubertal males. These combined findings have not been previously identified and are likely important results which indicate that females may develop increased risk of injury during puberty. The pubertal group was estimated at approximately 88% to 92% of adult stature during the first and second year of testing, respectively. These percent adult stature values indicate that the male and female subjects were at similar stages of somatic growth. Peak height velocity occurs at approximately 91% of adult stature in both male and females, with the onset of the adolescent growth spurt near 81 - 84%.[133] Therefore, the pubertal group appeared to be within the phase of rapid growth.

Within subject increases in knee abduction motion and moments are of particular concern given previous cadaveric and modeling work that have linked these measures to increased ACL strain.[28, 68, 134-138] In a recent cadaveric study, Withrow et al. simulated landings in ten specimens with knee abduction angles at 15° and 0°(neutral).[138] The impact with the knee in abduction led to a primary abduction (valgus) moment that increased ACL strain compared to the neutral landings. Shin et al. used a similar single leg landing impact that resulted in a knee abduction (valgus) moment to a three-dimensional dynamic knee model and found a 35% increase in ACL strain compared to a "neutral-lander" (zero knee abduction moment).[137] Based on incremental increase of the knee abduction moment, these authors showed that peak ACL strain increased rapidly between approximately 20 and 50 Nm.[137] While direct comparisons are difficult between modeling and *in vivo* data, I did find that post-pubertal females (21.9 Nm) were within the steepest region of ACL strain curve,[137] which indicates that slight increases in abduction moments would result in large increases in ligament strain. It is important to point out that all the knee loading conditions in this study were non-injurious (i.e. no injuries occurred during DVJ testing). However, it is likely that repeatedly performing a task with increased knee abduction moment and motion may place females at risk of an ACL injury when an unanticipated or unbalanced landing occurs. During unanticipated cutting, knee abduction-adduction and internal-external moments can be twice as high compared to pre-planned directional cutting.[12]

Mechanisms of growth and development in females may underlie the increased risk of ACL injury through altered movement biomechanics such as knee abduction.[36, 139] ACL injuries do not appear to be different between male and female athletes prior to the onset of puberty and the adolescent growth spurt.[30-33] However, following rapid pubertal growth, females have higher rates of knee sprains compared to males.[100] The lower extremity segments also go through rapid increases in length during adolescent growth and may potentially lead to increases in knee moments. Increased inertial properties of the segment (Table 3.2) could partially explain higher joint moments. Peak mass velocity for both sexes generally occurs after peak height velocity.[44] It is interesting that both male and females had increases in knee abduction moment, but knee abduction motion changes were found only in pubertal females. Therefore, growth alone is not likely to be responsible for the increased abduction motion in females. An additional mechanism that differs between sexes as they mature likely plays a role in increased risk of ACL injury in females compared to males. Fat mass remains relatively consistent in males, with skeletal tissue and muscle mass gains being primarily responsible for the observed mass increase.[44, 55] In contrast, females have less overall gains in skeletal tissue and muscle mass compared to males, in addition to a continuous rise in fat mass throughout puberty.[44, 55] The higher center of mass, that results from skeletal growth, and subsequent mass gain during adolescence, makes muscular control of body position more difficult and may translate into larger joint forces at the knee.[36] Males naturally demonstrate a "neuromuscular spurt" (increased strength and power during maturational growth and development) to match the increased demands of growth and development.[36, 51, 55, 140, 141] A recent longitudinal study concluded that males demonstrated a neuromuscular spurt as evidenced by increased vertical jump height and increased ability to attenuate landing force.[51] The absence of similar adaptations in females during maturation may facilitate the mechanisms that lead to increased risk of ACL injury.[101]

The timing of rapid growth may be the critical phase of development related to sex differences in ACL injury risk. As females reach maturity a variety of discrete sex differences in lower extremity measures have been shown in females compared to males performing landing and cutting maneuvers.[13-16, 36, 75, 82, 87, 122, 123] Sex differences between post-pubertal athletes, combined with the timing of the onset of these variables, indicates that an appropriate time to implement an intervention program would be during early puberty. A prospective study that will investigate the timing of intervention is warranted. Prevention programs that incorporate plyometrics, technique biofeedback, and dynamic balance components appear to be effective and reducing measures of knee abduction and the occurrence of ACL injuries.[27, 142, 143]

Conclusions

Knee abduction angle was significantly increased in pubertal females during rapid adolescent growth compared to males. In addition, important reported risk factors of knee abduction motion and torque were significantly greater across consecutive years in young female athletes, following rapid adolescent growth, compared to males. Early puberty appears to be an important phase related to potential increase risk of ACL injury based on the results of this longitudinal study as well, as from previous epidemiologic and cross-sectional studies. Future studies should focus on specific mechanisms that may limit or regulate dynamic abduction motion and torque, such as lower extremity strength, muscular co-contraction and joint stiffness parameters in young females that are at increased risk of ACL injury.

Table 3.1. Subject demographics

		Pubertal		Post-Pubertal	
		Female (n=145)	**Male (n=37)**	**Female (n=120)**	**Male (n=13)**
Year 1:	**Age (yrs)**	12.3 ± 0.8	13.0 ± 1.1	14.4 ± 1.4	15.1 ± 1.1
	Height (cm)	155.9 ± 6.8	165.2 ± 10.2	164.1 ± 6.1	180.8 ± 7.9
	Mass (kg)	47.8 ± 10.2	54.5 ± 10.2	59.0 ± 8.5	70.1 ± 8.4
Year 2:	**Age (yrs)**	13.3 ± 0.8	14.0 ± 1.1	15.4 ± 1.4	16.1 ± 1.1
	Height (cm)	160.7 ± 5.9	171.8 ± 9.2	165.2 ± 5.8	182.5 ± 7.6
	Mass (kg)	52.7 ± 9.9	61.1 ± 10.0	60.9 ± 8.7	74.9 ± 7.6

Table 3.2. Segment inertial parameters for female and male subjects

	X	Y	Z
Female			
Pelvis	0.1247*Mass* (0.433*RPV_SEG_LENGTH)^2	0.1247*Mass* (0.402*RPV_SEG_LENGTH)^2	0.1247*Mass* (0.444*RPV_SEG_LENGTH)^2
Thigh	0.1478*Mass* (0.369*RTH_SEG_LENGTH)^2	0.1478*Mass* (0.364*RTH_SEG_LENGTH)^2	0.1478*Mass* (0.162*RTH_SEG_LENGTH)^2
Shank	0.0481*Mass* (0.267*RSK_SEG_LENGTH)^2	0.0481*Mass* (0.263*RSK_SEG_LENGTH)^2	0.0481*Mass* (0.092*RSK_SEG_LENGTH)^2
Foot	(0.0129*Mass+0.3)* (0.299*ADJ_RFOOT_LENGTH)^2	(0.0129*Mass+0.3)* (0.139*ADJ_RFOOT_LENGTH)^2	(0.0129*Mass+0.3)* (0.279*ADJ_RFOOT_LENGTH)^2
Male			
Pelvis	0.1117*Mass* (0.615*RPV_SEG_LENGTH)^2	0.1117*Mass* (0.551*RPV_SEG_LENGTH)^2	0.1117*Mass* (0.587*RPV_SEG_LENGTH)^2
Thigh	0.1416*Mass* (0.329*RTH_SEG_LENGTH)^2	0.1416*Mass* (0.329*RTH_SEG_LENGTH)^2	0.1416*Mass* (0.149*RTH_SEG_LENGTH)^2
Shank	0.0433*Mass* (0.251*RSK_SEG_LENGTH)^2	0.0433*Mass* (0.246*RSK_SEG_LENGTH)^2	0.0433*Mass* (0.102*RSK_SEG_LENGTH)^2
Foot	(0.0137*Mass+0.3)* (0.257*ADJ_RFOOT_LENGTH)^2	(0.0137*Mass+0.3)* (0.124*ADJ_RFOOT_LENGTH)^2	(0.0137*Mass+0.3)* (0.245*ADJ_RFOOT_LENGTH)^2

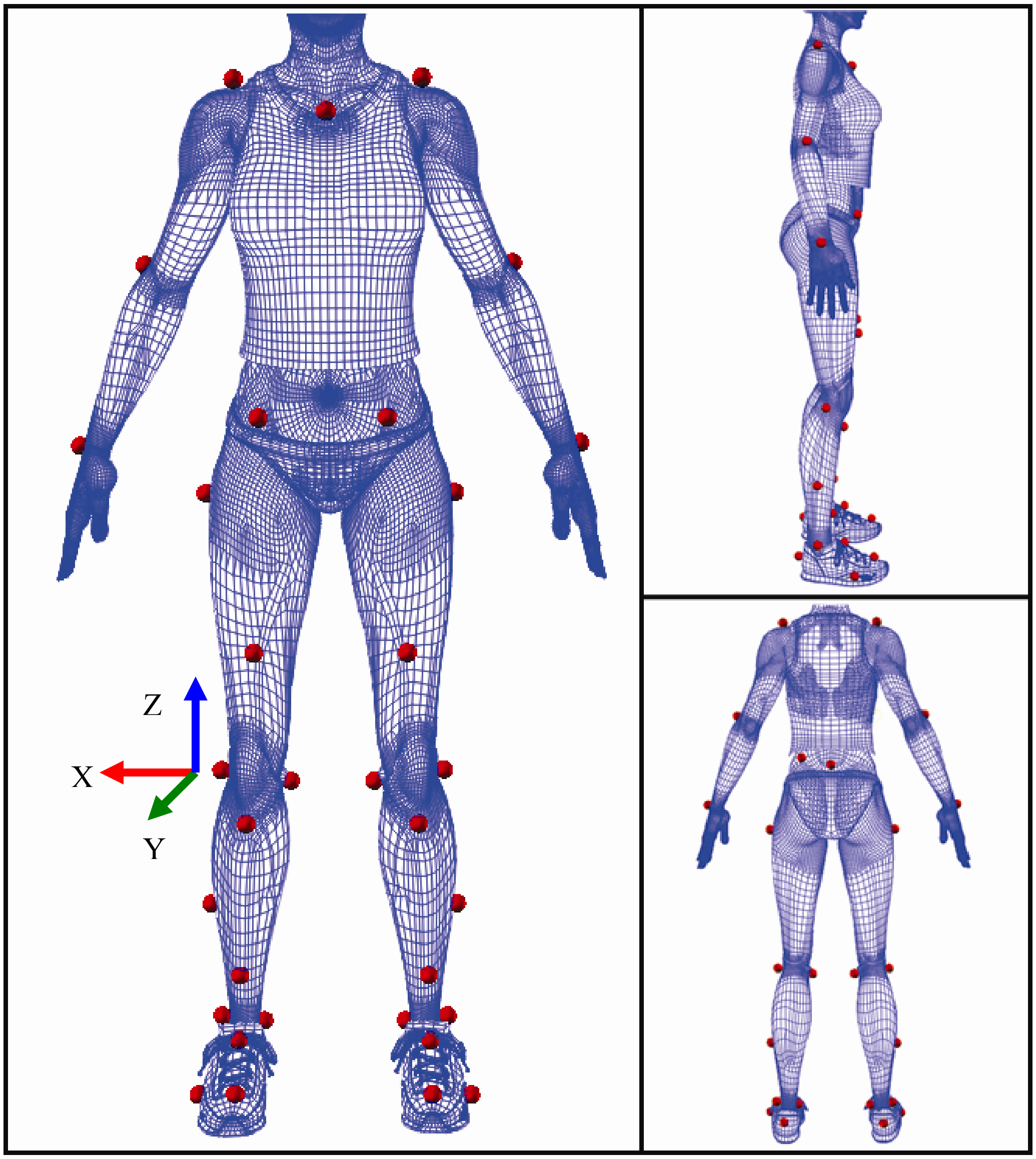


Figure 3.1. Locations of the retroreflective markers

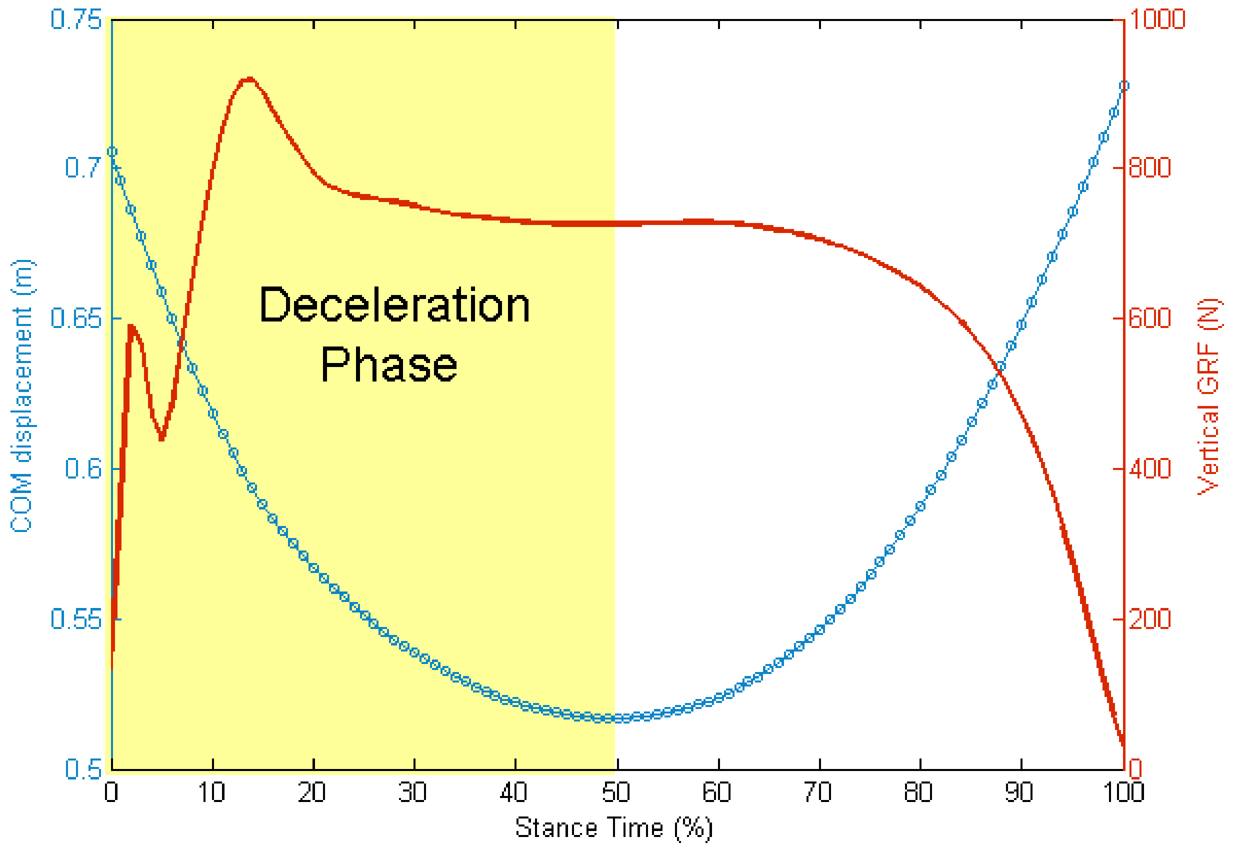


Figure 3.2. Identification of deceleration phase during drop vertical jump

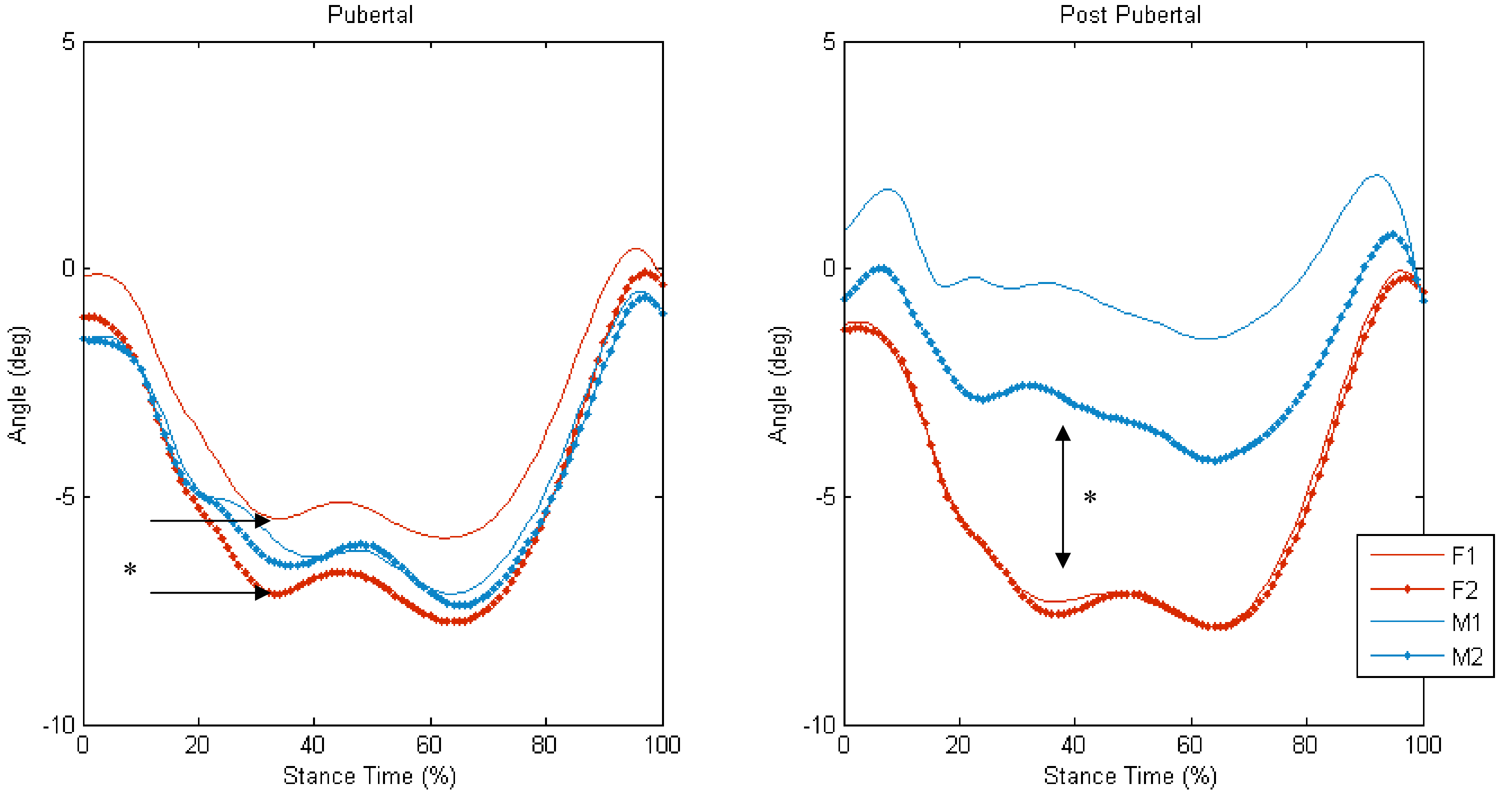


Figure 3.3. Mean knee abduction angle throughout the stance phase of the drop vertical jump.

Mean knee abduction angle for the pubertal (left) and post-pubertal (right) male and female athletes during the stance phase of the drop vertical jump. Negative values reflect increased external knee abduction angle. Female first year F1, female second year F2, male first year M1 and male second year M2. *Denotes statistically significant difference $p < 0.05$)

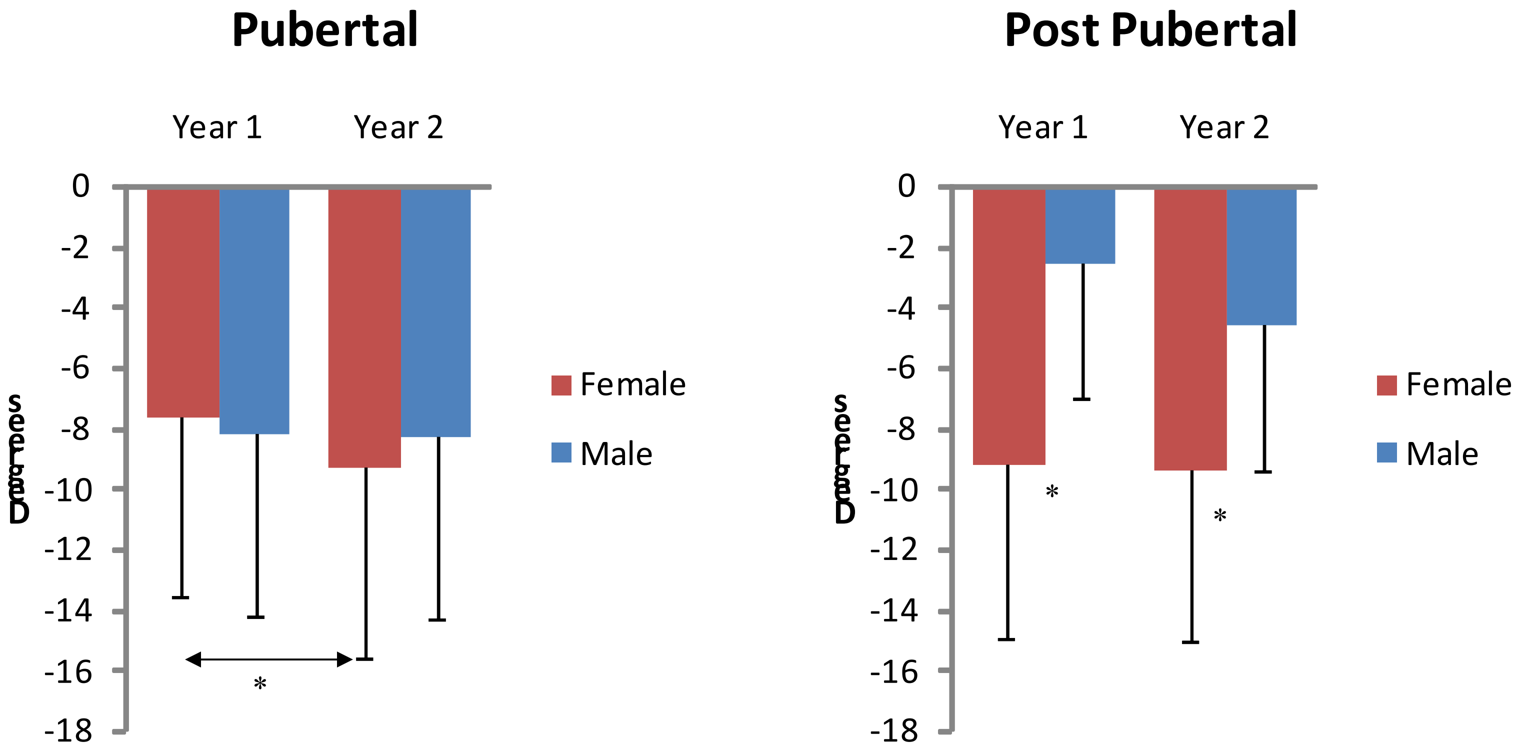


Figure 3.4. Peak knee abduction angle (mean and standard deviation) for the pubertal (left) and post-pubertal (right) male and female athletes.

*Denotes statistically significant difference $p < 0.05$)

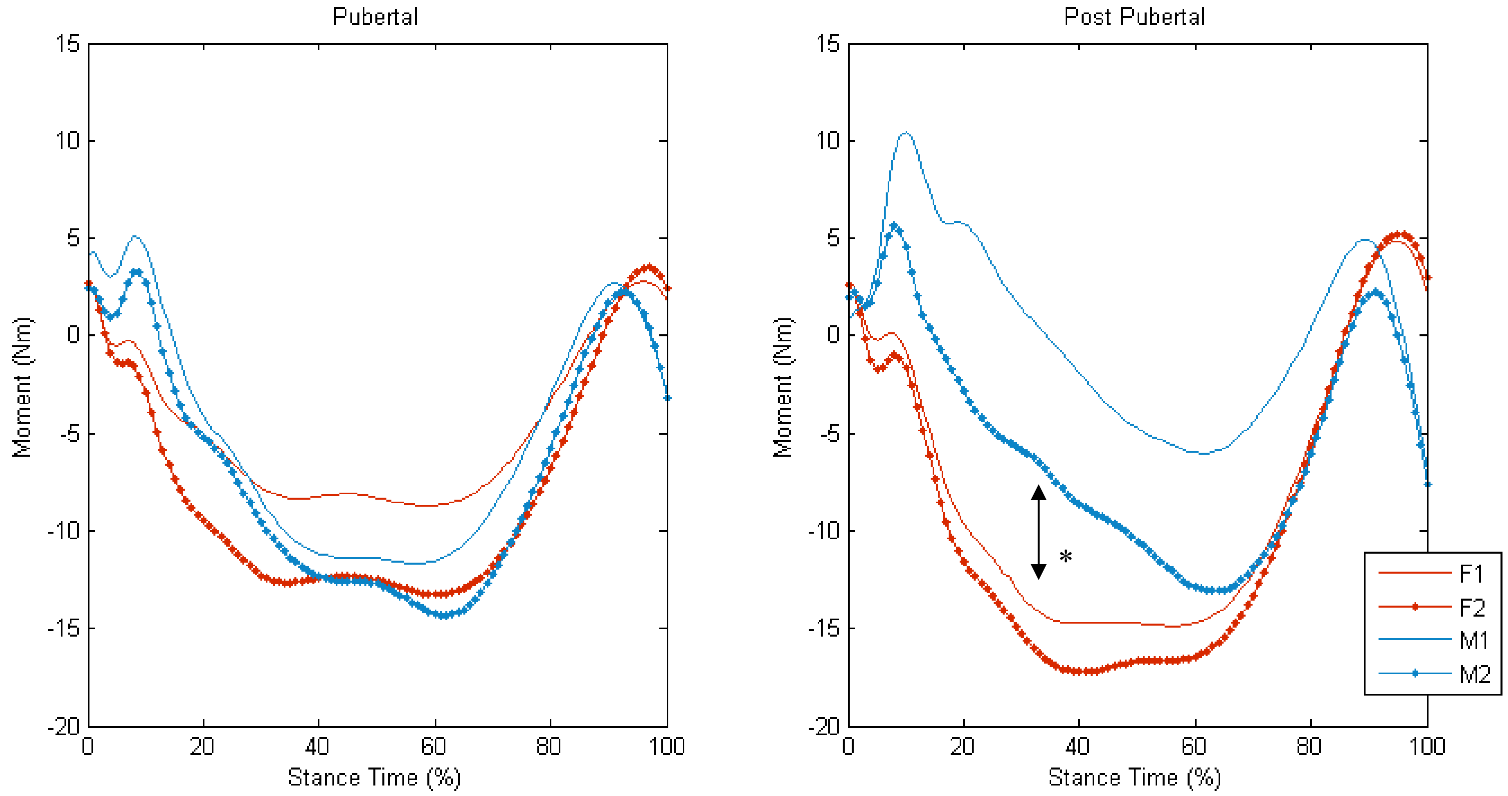


Figure 3.5. Mean knee external abduction moment throughout the stance phase of the drop vertical jump.

Mean knee abduction moment for the pubertal (left) and post-pubertal (right) male and female athletes during the stance phase of the drop vertical jump. Negative values reflect increased external knee abduction moment. Female first year F1, female second year F2, male first year M1 and male second year M2. *Denotes statistically significant difference $p < 0.05$)

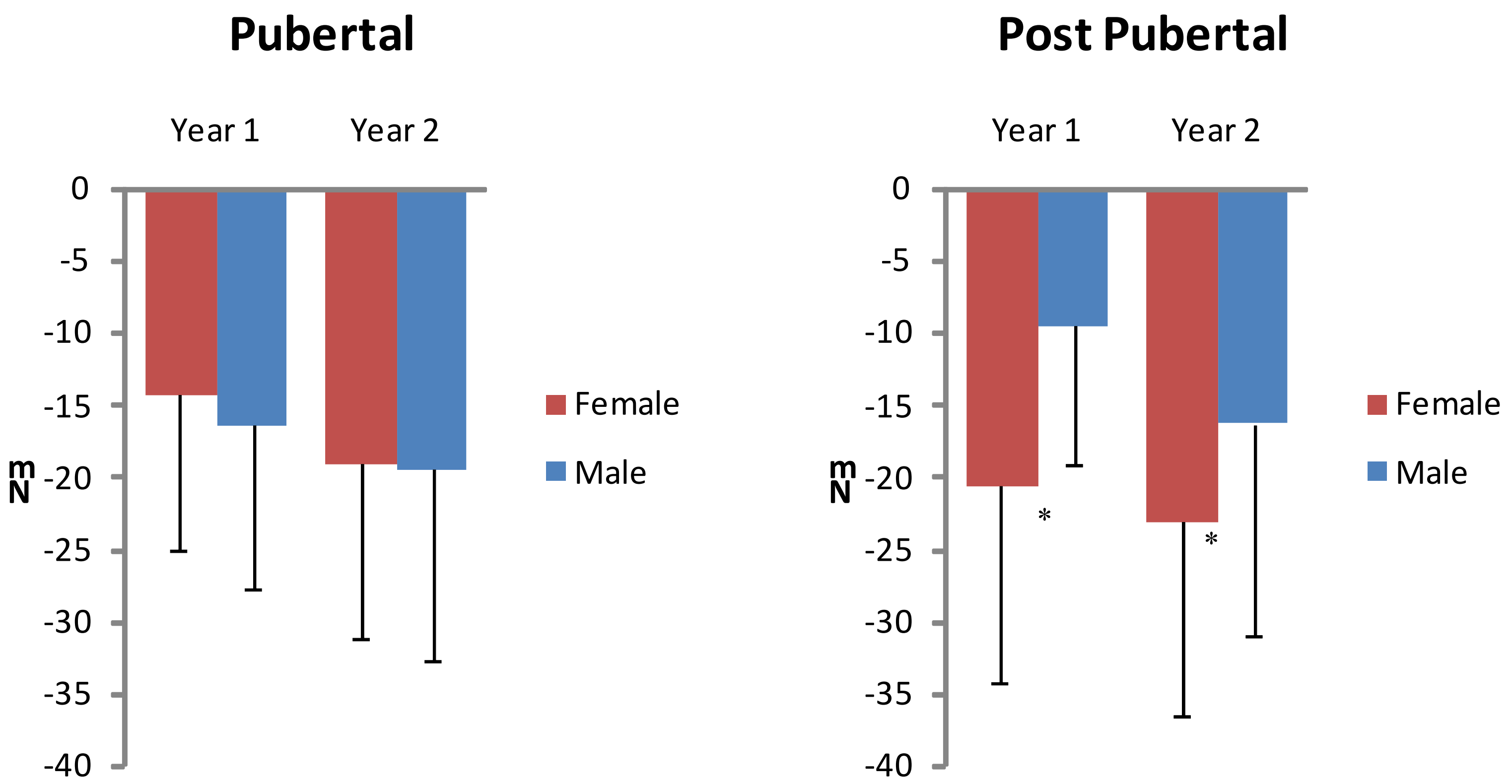


Figure 3.6. Peak knee abduction moment (mean and standard deviation) for the pubertal (left) and post-pubertal (right) male and female athletes.
*Denotes statistically significant difference $p < 0.05$)

Chapter 4. Active Joint Stiffness

Introduction

Females suffer anterior cruciate ligament (ACL) injuries at a 2 to 10-fold greater rate compared to male athletes participating in the same high-risk sports.[1-6] The combination of increased risk of injury and a 10-fold increase in the female sports population since the inception of Title IX has resulted in a dramatic increase in the number of ACL injuries in females.[5] Active joint stiffness has been suggested to be a potential neuromuscular risk factor that may at least partially explain the gender bias in ACL injuries.[35, 120, 144] Active joint stiffness can be voluntarily controlled through muscular recruitment and may increase dynamic joint stability.[120, 144, 145] Co-contraction of the flexor (hamstrings) and extensors (quadriceps) may protect the knee against altered movement patterns such as excessive knee abduction motion and torque. The knee flexor and extensor muscles are the primary knee joint stabilizers and are utilized during dynamic loading conditions to protect against an injury.[93] Strength and activation deficits of the hamstrings may limit the potential for muscular co-contraction to protect ligaments. Similar mechanisms apply to muscular protection against torsional loading, in which sex differences have been identified.[94] Decreased active stiffness (leg and knee) has been shown in females compared to males.[120, 146]

Hamstra-Wright et al.[147] examined leg stiffness during the DVJ in prepubertal subjects and found no sex differences. The effect of age on stiffness has been examined in a group of 6 year olds compared to 18 year olds.[148] As expected, they found increased stiffness at the ankle, knee and hip in the older group during countermovement vertical jumps.[148] They, however, did not include females in the study. In addition, the large gap in ages likely reflects multiple developmental, social and psychological factors that could influence the age differences found. Increased active joint stiffness may result in improved performance and possibly reduce the risk of ACL injury.[54, 59, 94, 119, 120, 144] However, it is important to realize that the optimal magnitude of joint stiffness is difficult to determine as either extreme (high or low) may result in poor performance or increased likelihood of load and injury. Joint stiffness variables are likely task specific, especially when considering a dynamic maneuver like a drop vertical jump that requires the athlete to immediately rebound from a drop to maximally jump.[54, 119]

Identifying the potential changes in active joint stiffness within each subject over the time span of a year may help explain when neuromuscular sex differences begin to emerge that may relate to increased ACL injury risk. The purpose was to determine if the neuromuscular risk factors related to knee stiffness diverge between the sexes during the adolescent growth spurt. The first hypothesis tested was that during rapid adolescent growth, pubertal males would have increases in knee stiffness while pubertal females would not. The second hypothesis was that post-pubertal females would have significantly lower knee joint stiffness compared to post-pubertal males.

Methods

Subjects

A nested cohort design (total sample female n = 709; total sample male n = 250) was used to select a subset of 315 subjects. The subjects were classified as either pubertal (n = 182) or post-pubertal (n = 133) based on the modified Pubertal Maturational

Observational Scale (PMOS) at each visit.[41] The PMOS is a reliable instrument that combines a parental questionnaire and investigator observations to classify subjects into the pubertal categories.[36, 51-53] Age, height and mass of the female and male subjects for two consecutive years are presented in Table 3.1. Each subject participated in the first testing session immediately before their basketball or soccer season. Two hundred and sixty one basketball players and 61 soccer players were tested. Approximately one year after the initial testing session (mean 365.7 ± 14.7 days) the subjects were retested using the exact same methods. Subjects were excluded from this study if they had previous history of knee or ankle surgery.

The data collection procedures were approved by Cincinnati Children's Hospital Institutional Review Board. Each parent or guardian reviewed and signed the Institutional Review Board approved consent to participate form prior to data collection. Child assent was also obtained from each subject prior to study participation. The database review and data analysis was certified exempt (Protocol No. 08-0928-X4B) under the University of Kentucky's Institutional Review Board based on federal regulation 45 CFR 46.101(b) for the protection of human subjects related to the study of existing data.

Procedures

Thirty-seven retroreflective markers were placed on each subject as previously described (Figure 3.1).[75] A static trial was collected in which the subject was instructed to stand still in the anatomical position with foot placement standardized. Three trials of the drop vertical jump (DVJ) were collected. The DVJ consisted of the subject starting on top of a 31 cm box with their feet positioned 35cm apart. They were instructed to drop directly down off the box and immediately perform a maximum vertical jump, raising both arms as if they were jumping for a basketball rebound.[15] Data trials were collected with EVaRT (Version 4, Motion Analysis Corporation, Santa Rosa, CA) using a motion analysis system with eight digital cameras (Eagle cameras, Motion Analysis Corporation, Santa Rosa, CA). The video data was collected at 240 Hz. The motion analysis system was calibrated based on manufacturer's recommendations. Two force platforms (AMTI, Watertown, MA) were embedded into the floor and positioned 8 cm apart so that each foot would contact a different platform during the stance phase of the DVJ. The force plate data were time synchronized with the motion analysis system and collected at 1200 Hz.

Data Analysis

Three-dimensional marker trajectories were examined for accurate marker identification within EVaRT (Version 4, Motion Analysis Corporation, Santa Rosa, CA) and exported to a C3D file format. The C3D files were then further analyzed in Visual3d (Version 4.0, C-Motion, Inc.). The procedures within Visual3D were described in detail previously (Chapter 3). Briefly, a pelvis and bilateral thigh, shank and foot segments were created based on the reflective markers. The mass and inertial properties for each segment were based on sex-specific parameters from de Leva.[126] and listed in detail in Table 3.2. The subject's height and mass were included in each model. Custom MATLAB code (Appendix D) was used to batch process each subject through the Visual3D pipeline. The code generated a text file that the Visual3D pipeline engine could read and process the subject-specific model and kinematic and kinetic analyses. 3D marker trajectories from each trial were filtered at a cutoff frequency of 12 Hz (low-pass fourth order Butterworth filter). 3D knee joint angles were calculated according to the cardan rotation sequence.[127] Kinematic data were combined with force data to calculate knee joint moments using inverse dynamics.[128, 129] The ground reaction force was filtered through a low-pass fourth order Butterworth filter at a cutoff frequency of 12 Hz in order to minimize possible impact peak errors.[130, 131] Net external knee moments are described in this paper and represent the external load on the joint. The kinematic and kinetic data were normalized to 101 points representing the stance phase of the DVJ. Data from initial contact (vertical ground reaction force first exceeded 10 N) to toe off (vertical ground reaction force fell below 10 N) was operationally defined as the stance phase (Figure 4.1). The right side data were used for statistical analysis.

Sagittal plane ankle, knee and hip angle and moments were used to calculate joint stiffness parameters.[54, 119] Joint stiffness was modeled based on a rotational spring for each joint. Rotational spring plots (joint moment as a function of joint angle) were calculated for each trial within MATLAB.[54, 149] Stiffness was calculated as the slope of the moment-angle curve from a least squares linear regression during the stance phase. Figure 4.2 shows an example of the variables calculated from the linear regression. In addition, the linearity of the curve was evaluated with the coefficient of determination (r^2).[119] Ankle dorsiflexion and knee and hip flexion were represented as positive values for consistent moment-angle curves. Ankle, knee and hip initial contact and peak flexion angles were calculated during the stance phase. Peak external flexion moments were also calculated during the DVJ stance.

Statistical Analysis

Two between group independent variables of sex (female, male) and maturation level (pubertal, post-pubertal) in addition to the within subject independent variable (repeated measure) of two consecutive year screening sessions were used in the statistical design. The dependent variables were ankle, knee and hip stiffness. A 2X2X2 ANOVA (maturation, sex, session) was used to test each hypothesis. Post-hoc analyses were used if significant interactions were found between factors. An $\alpha \leq 0.05$ was used to indicate statistical significance. Analyses were conducted using SPSS v16.0 (SPSS Inc., Chicago, IL).

Results

Stiffness

Active joint stiffness variables are presented in Table 4.1. The coefficient of determination was high for each joint (Table 4.1). The linear regression fit ranged from $r^2 = 0.74 \pm 0.30$ to $r^2 = 0.87 \pm 0.14$. Ankle, knee and hip stiffness increased from the first to the second year of testing in both male and females (main effect of year, ankle $p = 0.001$, knee $p = 0.043$, hip $p < 0.001$) (Figure 4.3). In addition, a significant interaction with year and maturation level was found at the ankle ($p = 0.05$) and hip ($p = 0.006$). Post-hoc analyses indicated that increased ankle and hip stiffness was evident in the pubertal group ($p < 0.001$) but not in the post-pubertal ($p > 0.05$) from the first to second year. Significant interaction (year * maturation) trended towards the same results with knee stiffness, but was not statistically significant ($p = 0.085$). However, when the joint moments were normalized to body mass (Figure 4.4), the differences in ankle, knee and hip stiffness between years were not statistically different ($p > 0.05$).

Figure 4.5 shows the calculated stiffness comparison of post-pubertal males and females. Males had significantly greater active stiffness at the ankle, knee and hip compared to females ($p < 0.001$, Table 4.1). However, when joint moments were normalized to body mass, knee stiffness was not significantly different between sexes (total female 0.029 ± 0.011 Nm/kg·°, total male 0.031 ± 0.013 Nm/kg·°, $p = 0.223$) (Figure 4.4). Body mass normalized ankle (total female 0.023 ± 0.008 Nm/kg·°, total male 0.028 ± 0.010 Nm/kg·°, $p < 0.001$) and hip (total female 0.033 ± 0.008 Nm/kg·°, total male 0.046 ± 0.013 Nm/kg·°, $p < 0.001$) stiffness were still significantly greater in males compared to females. In addition, an interaction with sex and maturational group was found with both normalized ($p = 0.007$) and non-normalized ($p = 0.001$) hip stiffness with the post-pubertal males exhibiting significantly greater hip stiffness than the other groups (Figure 4.3).

Joint Angles and Moments

Ankle, knee and hip kinematic and kinetic variables are displayed in Table 4.2 and Table 4.3. All subjects combined demonstrated significantly increased peak knee and hip flexion angles from the first year of testing to the second (knee $p = 0.034$, hip $p = 0.015$). The magnitude of the difference was small in both male and female subjects (knee: female 0.7 ± 7.1°, male 1.9 ± 5.4°; hip: female 1.9 ± 7.9°, male 1.7 ± 7.4°). No other kinematic variables at initial contact or peak were different between testing years ($p > 0.05$). Overall, females landed at initial contact with less hip flexion compared to males (main effect of sex $p = 0.035$). In addition, females had significantly increased peak ankle dorsiflexion (main effect of sex $p = 0.001$) and knee flexion angle (main effect of sex $p = 0.001$) compared to males (main effect of sex $p = 0.001$). No interactions or differences in kinematic variables were found among maturational groups ($p > 0.05$).

Males had significantly increased ankle and hip peak moments from the first year of testing to the second compared to females (sex*year interaction: ankle $p = 0.001$, hip $p = 0.01$, Table 4.3). There was not a significant interaction of sex and consecutive tests with external knee flexion moment ($p > 0.05$). Both male and females increased external knee flexion moment during consecutive years (main effect of year, $p < 0.001$).

Peak ankle and hip moments in post-pubertal males were significantly greater than post-pubertal females (sex*maturation interaction: ankle $p = 0.025$, hip $p = 0.001$, Table 4.3). When normalized to body mass the males had significantly greater ankle and hip moments while no differences were found in knee moments (Table 4.4, Figure 4.6). The ratio of peak knee to peak hip external moment was different between males and females ($p < 0.001$). Females utilized greater external knee flexion moment while males had more relative external hip flexion moments (Figure 4.7).

Discussion

Active joint stiffness was theorized as a possible regulatory mechanism to stabilize the joint and control dangerous movement patterns that may place females at higher risk of injury. Joint stiffness calculations involve the resistance of a mechanical stretch by an applied force.[59] Knee flexor and extensor muscles are the primary knee joint stabilizers that may protect against an injury during dynamic loading conditions.[93] Males and females both had increases in DVJ active knee stiffness during the span of a year. Therefore, the present findings did not support the hypothesis that females would not increase knee stiffness during a year of pubertal growth. However, ankle and hip active stiffness was significantly increased from the first year of testing to the second year in males compared to females. Only one previous study was found that investigated active joint stiffness differences between maturational groups. Joint stiffness was increased in older male subjects (18 year old) compared to children (6 year old) during a countermovement vertical jump.[148] In addition, Hamstra-Wright et al.[147] examined leg stiffness during the DVJ in prepubertal subjects and found no sex differences.

Similar to the previous work of Padua et al.[59], we found that females had significantly reduced stiffness compared to males. This supports my hypothesis that knee stiffness would be lower in females. However, like Padua et al.[59], when normalized to body mass the sex differences in active knee stiffness were no longer apparent. Changes to active joint stiffness can be accomplished, simplistically, through altering the joint moment magnitude and/or joint angular displacement. Although male and female athletes had similar normalized knee stiffness parameters, the maximum knee flexion angle was significantly greater in females compared to males. Increases in the normalized external net knee flexion moment may be responsible for the normalized stiffness parameters remaining similar in females. A quadriceps dominant recruitment pattern was supported in females that utilized this strategy to modulate stiffness parameters compared to males during hopping.[59] While we did not measure muscular activation patterns, a similar quadriceps dominant pattern could be interpreted based on the relationship of external knee flexor to hip flexor moment. We found a significantly higher ratio of external knee flexor moment (internal extensor) to external hip flexor moment (internal extensor) in females, while males were more balanced. Even when normalized to body mass, post-pubertal males had significantly greater external hip flexor moments compared to females. It is particularly interesting that no sex differences were found in external knee flexor (quadriceps dominated) moment. During the DVJ the knee extensors are utilized to resist the external flexion moment. Internal ankle and hip extensor moments are dominated by bi-articular muscles that function as knee flexors. Two scenarios are likely to help interpret the absence of sex differences in knee flexion moment with greater ankle and hip moments in males: 1) females had increased knee extensor force or 2) males had increased knee flexor force. Therefore, even if males had larger overall knee extensor forces, compared to females, the net moment could be equal based on co-contraction of knee antagonist muscles.

Adequate antagonist co-contraction (knee flexors) may balance quadriceps activation, compress the joint, and control high knee extension and abduction torques immediately after ground contact.[11] Muscular co-contraction compresses the joint, due in part to the concavity of the medial tibial plateau, which may protect the ACL against anterior drawer.[150] Increased balance in strength and recruitment of the flexor relative to the extensor musculature may protect the ACL.[11] If hamstrings recruitment is high, the quadriceps can be activated to a greater extent while still allowing for a net flexor moment and similar mechanisms apply to activation strategies to protect sex differences that have been identified in torsional loading.[94] Wojtys et al. demonstrated that maximal internal rotations of the tibia (transverse plane) were greater in females than in males in both the passive and the active muscle state.[94] Females exhibited less muscular protection of the knee ligaments under internal rotation loading than did males.[94] Muscular activation patterns during landing has also shown an increased reliance on the quadriceps in female athltes.[151] During single leg landing maneuvers females increased quadriceps while decreasing gluteus maximus activity compared to males.[151]

The greater ankle and hip moments in post-pubertal males likely explain the greater ankle and hip stiffness compared to females. Post-pubertal males had significantly larger active ankle and hip stiffness compared to the other groups, in both normalized and un-normalized values. This may indicate that post-pubertal males landed with a different neuromuscular strategy to control the landing and push-off phase of DVJ than the other groups. Increased internal hip extensor moments have been shown previously during the DVJ in males compared to females.[50] Decker et al.[110] showed that during a drop landing males utilized the hip more for energy absorption compared to females. Significant sex differences in knee abduction motion and moments were found in the post-pubertal athletes as reported in Chapter 3. Post-pubertal males had lower normalized external knee abduction angles and moments compared to females. The relationship between increased ankle and hip stiffness and decreased knee abduction measures will be presented in Chapter 5.

Females landed at initial contact with decreased hip flexion compared to males. This may play an important role in the mechanical efficiency of the hamstrings muscles in relation to the quadriceps.[152] For example, the trunk may be positioned over the knee more with increased hip flexion, which has been indicated to increase activation of the hamstrings compared to a posterior trunk position.[152, 153]

Increased stiffness appears to coincide with increased performance.[119, 148] Vertical jump height increased with increased stiffness in males performing the DVJ.[119] However, there is likely an optimum level of stiffness for both performance and injury prevention.[154] Decreased stiffness that may result in decreased performance, while stiffness too high may lead to excessive loading rates and possible injury.[154] The relationship between stiffness and performance should be investigated further within female and male athletes.

The torsional spring model appeared to be an appropriate representation during the DVJ, with high linear correlations of the moment-angle relationship throughout the stance phase. The correlations ranged from $r = 0.86$ to $r = 0.93$. These values are similar to Stefanyshyn and Nigg,[54] who found average ankle stiffness linear correlations of $r = 0.86$ during running and $r = 0.93$ for sprinting. During single leg hopping at different frequencies, Granata et al. found correlations between vertical displacement and vertical ground reaction force that ranged between $r = 0.92$ and $r = 0.96$. In addition, during drop jumps, ankle stiffness models have reported linear correlations of $r = 0.88$ to $r = 0.99$ and knee stiffness correlations between $r = 0.65$ and $r = 0.93$.[119]

Our measure of active joint stiffness is actually quasi-stiffness, defined by Latash and Zatsiorsky[155] as the "…ability of the system to resist externally imposed displacements disregarding the time course of the displacement." A limitation of this simplistic model is that it ignores multiple components of the multi-joint system (i.e. viscosity, muscle reflex time delays, degrees of freedom, tendons, bones etc.). An additional and related limitation of modeling active joint stiffness based on the spring-mass model is the use of external joint moments. Calculation of joint moments through inverse dynamics incorporates the *net* forces that act about the joint.[116] Net joint moments do not show which muscles are active or the magnitude of individual muscle forces generated at any specific point in time. Unfortunately, without sophisticated modeling of muscle forces, or possibly via electromyographical methods, we are unable to fully interpret the isolated net external knee flexion moment. Therefore, cautious interpretation of the joint moment relative to the actual muscle forces is necessary.

Conclusions

Males and females both showed increased active knee stiffness during the span of a year. However, ankle and hip active stiffness were significantly increased in males compared to females. Sex differences in ankle and hip stiffness may begin to occur slightly prior to the adolescent growth spurt. Follow-up studies should address prepubertal athletes to identify if sex differences exist prior to peak height velocity.

When normalized to body mass, there were no differences between testing years. This indicates that progressive increases in body mass during adolescence may play a role in active joint stiffness. Despite the results of the longitudinal change, post-pubertal males exhibited greater hip stiffness than females. Sex differences in hip joint posture at initial contact and external hip flexion moment may indicate that males utilize a different hip strategy during drop vertical jumps compared to females. The impact of a hip focused intervention, and the relationship that active joint stiffness has on altered movement patterns, should be further explored in adolescent females and males.

Table 4.1. Stiffness parameters for ankle, knee and hip joints.

			Pubertal		Post-Pubertal	
			Female (n=145)	Male (n=37)	Female (n=120)	Male (n=13)
Ankle	**Stiffness (Nm/°)**[a,b,c,d]	**Year 1**	1.03 ± 0.45	1.47 ± 0.56	1.38 ± 0.49	2.01 ± 0.67
		Year 2	1.19 ± 0.44	1.70 ± 0.69	1.46 ± 0.51	2.05 ± 0.83
	Intercept (Nm)	**Year 1**	36.1 ± 10.3	48.1 ± 13.4	46.4 ± 10.7	63.6 ± 21.0
		Year 2	41.5 ± 11.2	56.6 ± 16.1	48.9 ± 11.6	71.7 ± 19.1
	r^2	**Year 1**	0.794 ± 0.183	0.839 ± 0.147	0.852 ± 0.164	0.783 ± 0.178
		Year 2	0.837 ± 0.145	0.788 ± 0.186	0.865 ± 0.146	0.739 ± 0.296
Knee	**Stiffness (Nm/°)** [a,b,c]	**Year 1**	1.40 ± 0.66	1.63 ± 0.81	1.72 ± 0.72	2.31 ± 0.83
		Year 2	1.52 ± 0.62	1.89 ± 0.78	1.77 ± 0.68	2.30 ± 0.94
	Intercept (Nm)	**Year 1**	-27.4 ± 21.4	-29.4 ± 22.4	-31.0 ± 24.7	-42.3 ± 29.7
		Year 2	-29.3 ± 20.7	-34.0 ± 23.8	-32.9 ± 22.8	-47.8 ± 30.5
	r^2	**Year 1**	0.853 ± 0.121	0.864 ± 0.136	0.859 ± 0.154	0.868 ± 0.127
		Year 2	0.869 ± 0.110	0.871 ± 0.144	0.874 ± 0.135	0.839 ± 0.155
Hip	**Stiffness (Nm/°)** [a,b,c,d,f]	**Year 1**	1.50 ± 0.44	2.42 ± 0.94	2.03 ± 0.49	3.57 ± 0.60
		Year 2	1.70 ± 0.49	2.70 ± 1.04	2.05 ± 0.51	3.63 ± 0.81
	Intercept (Nm)	**Year 1**	-29.8 ± 12.9	-34.8 ± 22.4	-44.9 ± 17.3	-56.0 ± 22.3
		Year 2	-35.8 ± 15.9	-37.7 ± 25.2	-45.5 ± 17.4	-55.9 ± 35.4
	r^2	**Year 1**	0.774 ± 0.130	0.825 ± 0.103	0.758 ± 0.116	0.805 ± 0.101
		Year 2	0.786 ± 0.111	0.822 ± 0.099	0.779 ± 0.099	0.810 ± 0.115

[a]Denotes statistically significant effect of year ($p < 0.05$), [b]Denotes statistically significant effect of sex ($p < 0.05$), [c]Denotes statistically significant effect of maturation ($p < 0.05$), [d]Denotes statistically significant interaction of year and maturation ($p < 0.05$), [e]Denotes statistically significant interaction of year and sex ($p < 0.05$), [f]Denotes statistically significant interaction of sex and maturation ($p < 0.05$)

Table 4.2. Ankle, knee and hip kinematics at initial contact and peak flexion.

			Pubertal		Post-Pubertal	
			Female (n=145)	**Male (n=37)**	**Female (n=120)**	**Male (n=13)**
Ankle	**IC (°)**	**Year 1**	-24.0 ± 6.8	-24.5 ± 7.4	-24.9 ± 6.1	-24.2 ± 4.9
		Year 2	-24.6 ± 6.8	-25.9 ± 4.6	-24.9 ± 5.7	-24.1 ± 4.4
	Peak (°) [b]	**Year 1**	30.3 ± 4.9	27.1 ± 5.0	29.1 ± 4.8	26.8 ± 6.3
		Year 2	30.1 ± 5.1	27.1 ± 4.8	29.3 ± 4.6	27.4 ± 5.2
Knee	**IC (°)**	**Year 1**	22.9 ± 7.4	21.3 ± 7.5	22.0 ± 6.8	24.3 ± 6.8
		Year 2	22.6 ± 7.2	21.1 ± 6.9	21.8 ± 5.9	24.4 ± 8.2
	Peak (°) [a,b]	**Year 1**	83.1 ± 8.9	78.5 ± 9.5	81.2 ± 8.1	78.7 ± 9.2
		Year 2	83.9 ± 9.1	80.5 ± 10.8	81.9 ± 7.7	80.3 ± 8.0
Hip	**IC (°)** [b]	**Year 1**	26.9 ± 8.1	28.5 ± 8.3	26.9 ± 8.1	29.9 ± 9.3
		Year 2	27.4 ± 7.1	28.2 ± 7.5	26.8 ± 6.8	31.5 ± 9.3
	Peak (°) [a]	**Year 1**	56.6 ± 9.2	54.8 ± 9.6	56.1 ± 8.9	55.3 ± 9.2
		Year 2	57.7 ± 8.3	55.9 ± 12.2	57.3 ± 8.9	58.4 ± 8.4

[a]Denotes statistically significant effect of year ($p < 0.05$), [b]Denotes statistically significant effect of sex ($p < 0.05$), [c]Denotes statistically significant effect of maturation ($p < 0.05$), [d]Denotes statistically significant interaction of year and maturation ($p < 0.05$), [e]Denotes statistically significant interaction of year and sex ($p < 0.05$), [f]Denotes statistically significant interaction of sex and maturation ($p < 0.05$)

Table 4.3. Ankle, knee and hip peak joint moments.

			Pubertal		Post-Pubertal	
			Female (n=145)	**Male (n=37)**	**Female (n=120)**	**Male (n=13)**
Ankle	**Peak (Nm)** [a,b,c,e,f]	**Year 1**	73.1 ± 20.8	95.2 ± 26.5	91.1 ± 20.7	126.4 ± 23.8
		Year 2	81.6 ± 20.9	110.3 ± 28.0	95.0 ± 22.2	142.5 ± 27.4
Knee	**Peak (Nm)** [a,b,c,d]	**Year 1**	91.1 ± 24.5	101.6 ± 31.0	113.8 ± 29.2	142.1 ± 28.4
		Year 2	100.4 ± 25.5	122.3 ± 30.0	115.5 ± 28.1	143.1 ± 33.7
Hip	**Peak (Nm)** [a,b,c,e,f]	**Year 1**	71.5 ± 18.8	109.6 ± 30.4	91.2 ± 22.3	151.8 ± 19.7
		Year 2	80.9 ± 21.0	124.5 ± 35.0	94.1 ± 23.9	165.1 ± 27.1

[a] Denotes statistically significant effect of year ($p < 0.05$), [b] Denotes statistically significant effect of sex ($p < 0.05$), [c] Denotes statistically significant effect of maturation ($p < 0.05$), [d] Denotes statistically significant interaction of year and maturation ($p < 0.05$), [e] Denotes statistically significant interaction of year and sex ($p < 0.05$), [f] Denotes statistically significant interaction of sex and maturation ($p < 0.05$)

Table 4.4. Normalized peak joint moments

			Pubertal		Post-Pubertal	
			Female (n=145)	**Male (n=37)**	**Female (n=120)**	**Male (n=13)**
Ankle	**Peak (Nm) [b]**	**Year 1**	1.46 ± 0.36	1.62 ± 0.35	1.47 ± 0.32	1.64 ± 0.33
		Year 2	1.48 ± 0.33	1.65 ± 0.43	1.49 ± 0.29	1.68 ± 0.41
Knee	**Peak (Nm) [d]**	**Year 1**	1.91 ± 0.40	1.85 ± 0.45	1.93 ± 0.43	1.96 ± 0.35
		Year 2	1.90 ± 0.37	1.98 ± 0.43	1.89 ± 0.00	1.84 ± 0.42
Hip	**Peak (Nm) [b]**	**Year 1**	1.50 ± 0.39	1.96 ± 0.42	1.53 ± 0.36	2.08 ± 0.35
		Year 2	1.54 ± 0.39	1.98 ± 0.47	1.54 ± 0.38	2.16 ± 0.31

[a]Denotes statistically significant effect of year ($p < 0.05$), [b]Denotes statistically significant effect of sex ($p < 0.05$), [c]Denotes statistically significant effect of maturation ($p < 0.05$), [d]Denotes statistically significant interaction of year and maturation ($p < 0.05$), [e]Denotes statistically significant interaction of year and sex ($p < 0.05$), [f]Denotes statistically significant interaction of sex and maturation ($p < 0.05$)

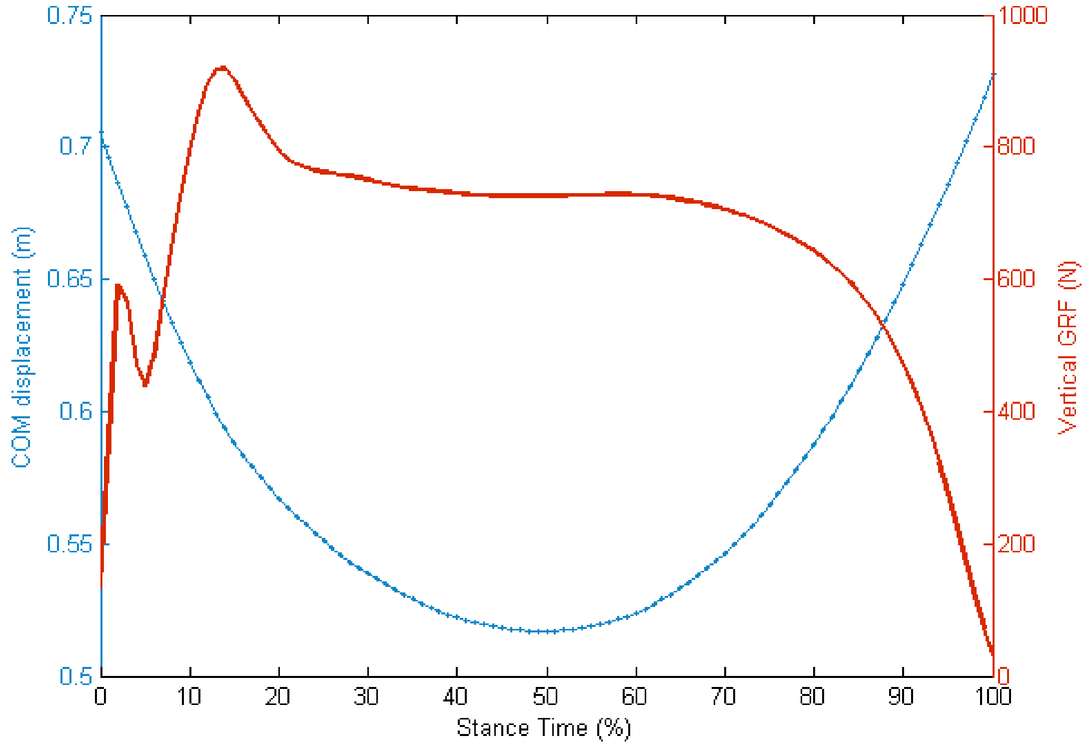


Figure 4.1. Identification COM displacement and GRF during the stance phase (0 – 100%) of a drop vertical jump

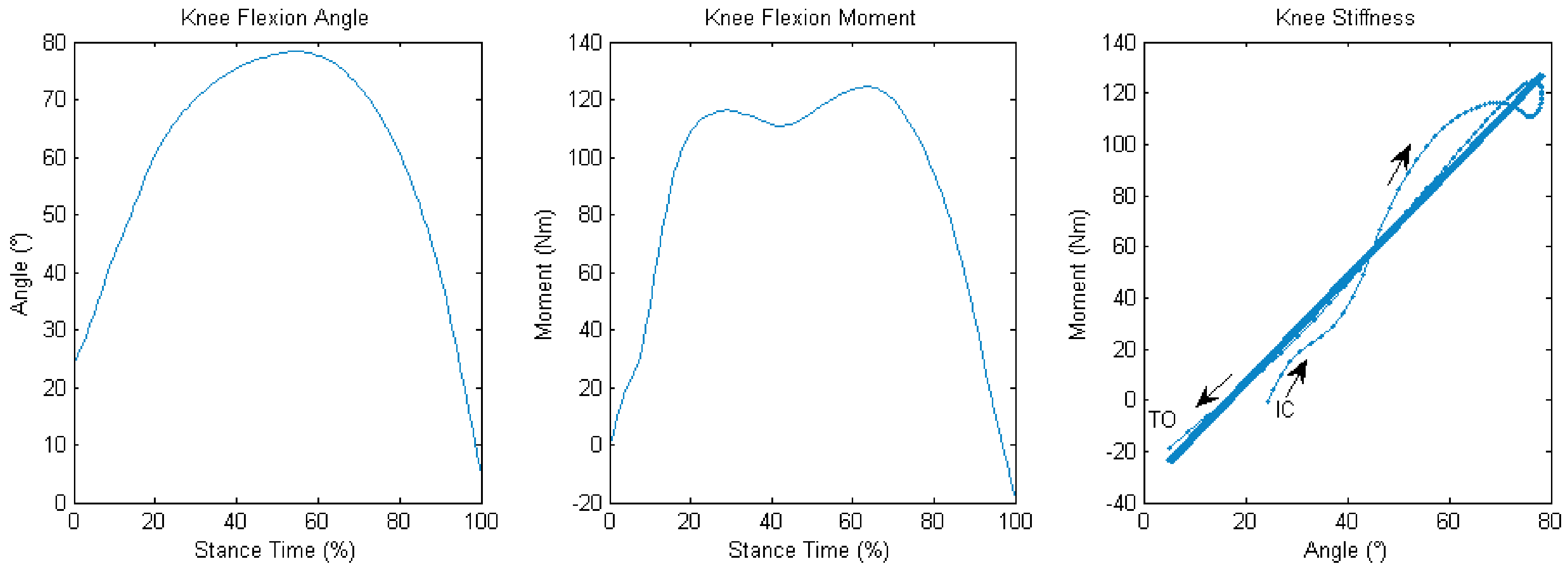


Figure 4.2. Calculation of knee stiffness based on moment-angle plot (note: knee flexion angle and moment are inversed in order to compare to ankle and hip variables). Note: the moment-angle plot starts at initial contact (IC) and finishes at toe off (TO).

Linear regression equation($y = 2.1*x - 35$*) for the moment-angle plot. The coefficent of determination (* $r^2 = 0.95$*) represents the linear fit of the spring mass model. The slope (2.1 Nm/°) and the intercept (-35 Nm) are also calculated.*

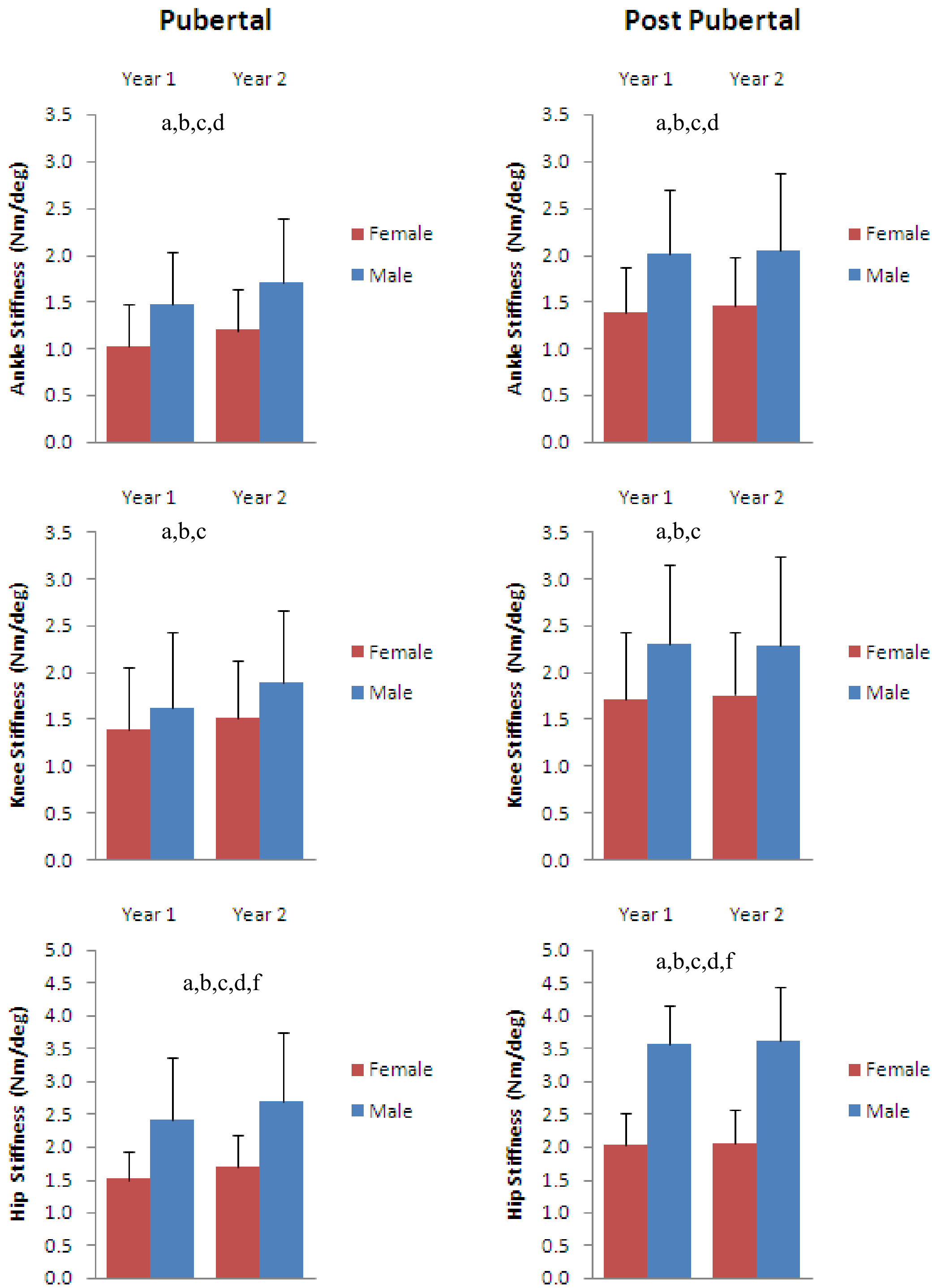


Figure 4.3. Joint stiffness for the ankle, knee and hip
[a]Denotes statistically significant effect of year ($p < 0.05$), [b]Denotes statistically significant effect of sex ($p < 0.05$), [c]Denotes statistically significant effect of maturation ($p < 0.05$), [d]Denotes statistically significant interaction of year and maturation ($p < 0.05$), [f]Denotes statistically significant interaction of sex and maturation ($p < 0.05$)

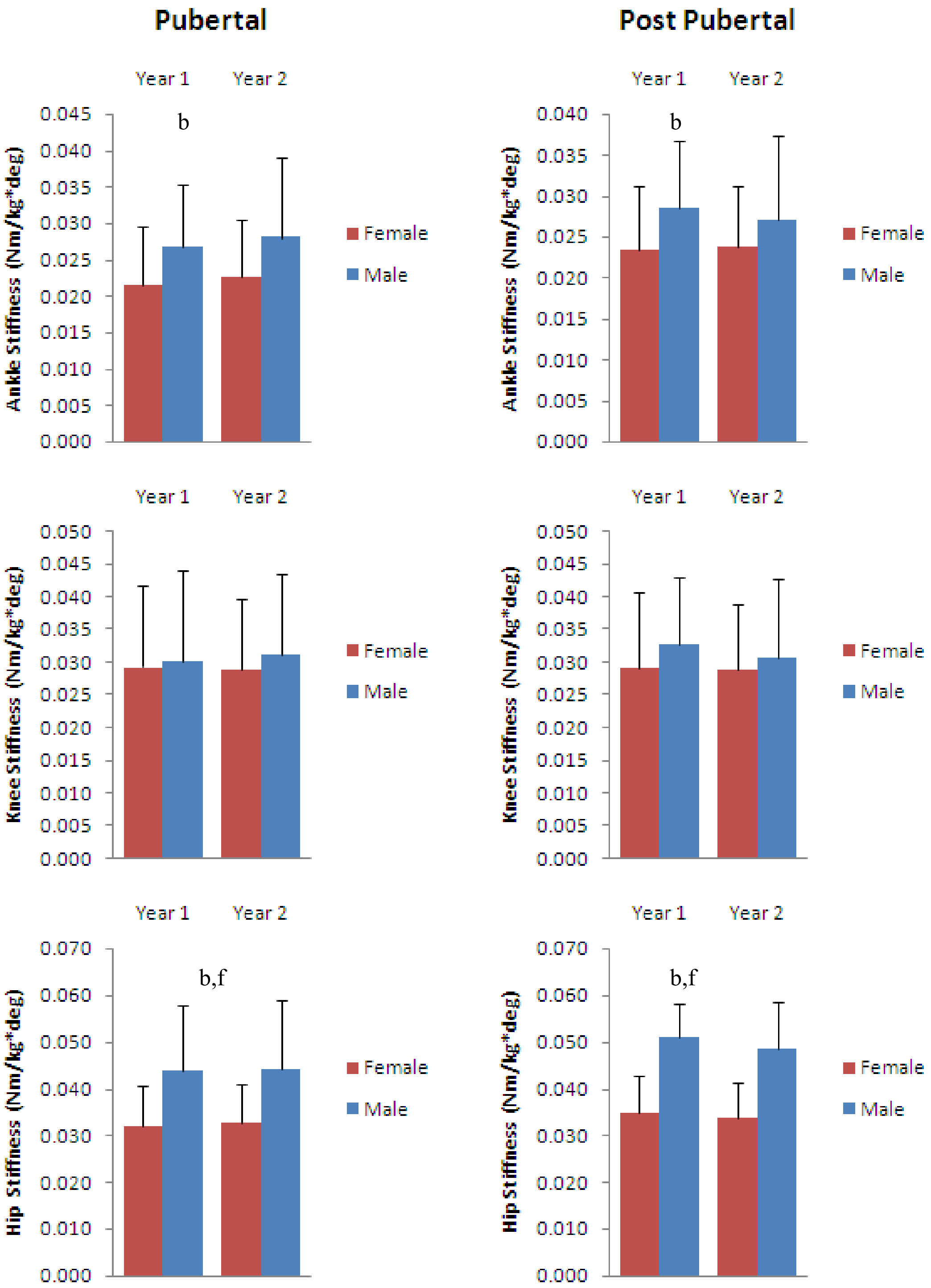


Figure 4.4. Normalized joint stiffness for the ankle, knee and hip
[b]Denotes statistically significant effect of sex ($p < 0.05$), [f]Denotes statistically significant interaction of sex and maturation ($p < 0.05$)

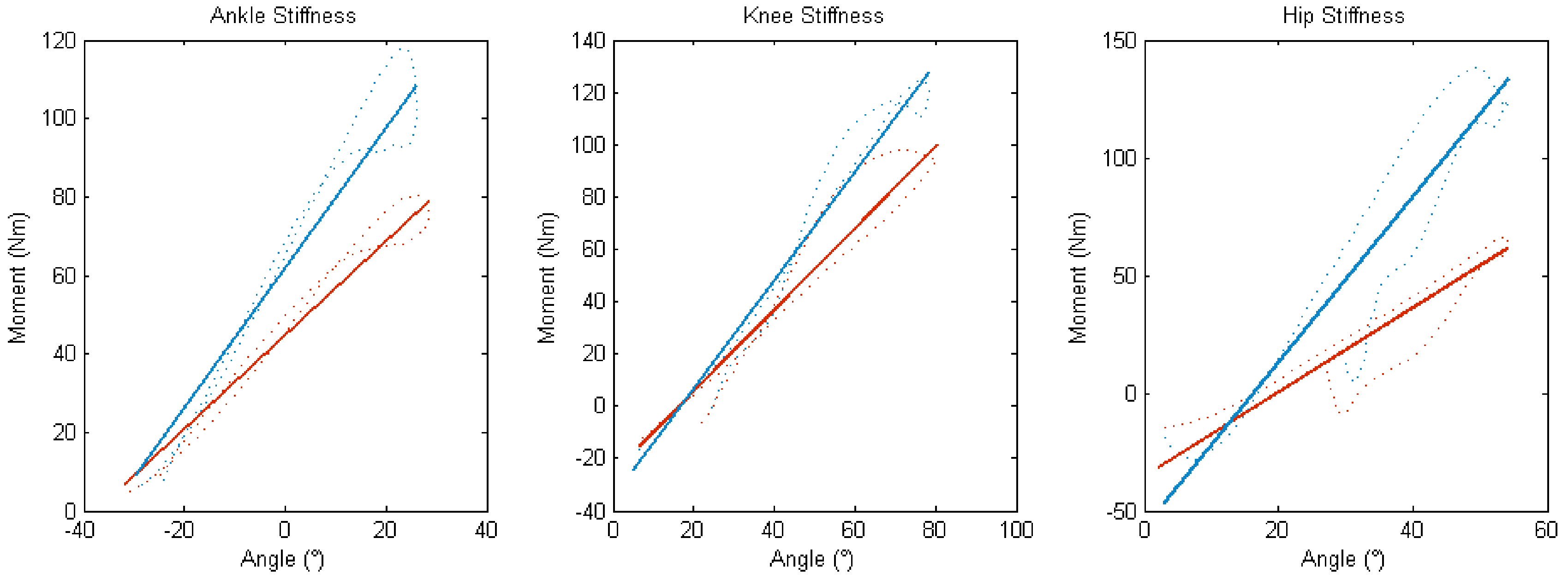


Figure 4.5. Moment-angle plots (dotted lines) of the ankle, knee and hip with estimated joint stiffness (solid line) based on the slope of the least squares regression.

The regression plots were based on ensemble averages of post-pubescent female (red) and male (blue) subjects. Ankle equations female: $y = 1.2*x + 45$, $r^2 = 0.95$*; male:* $y = 1.8*x + 62$, $r^2 = 0.89$*. Knee equations female:* $y = 1.6*x - 26$, $r^2 = 0.92$*; male:* $y = 2.1*x - 35$, $r^2 = 0.95$*. Hip equations female:* $y = 1.8*x - 36$, $r^2 = 0.86$*; male:* $y = 3.5*x -57$, $r^2 = 0.85$*.*

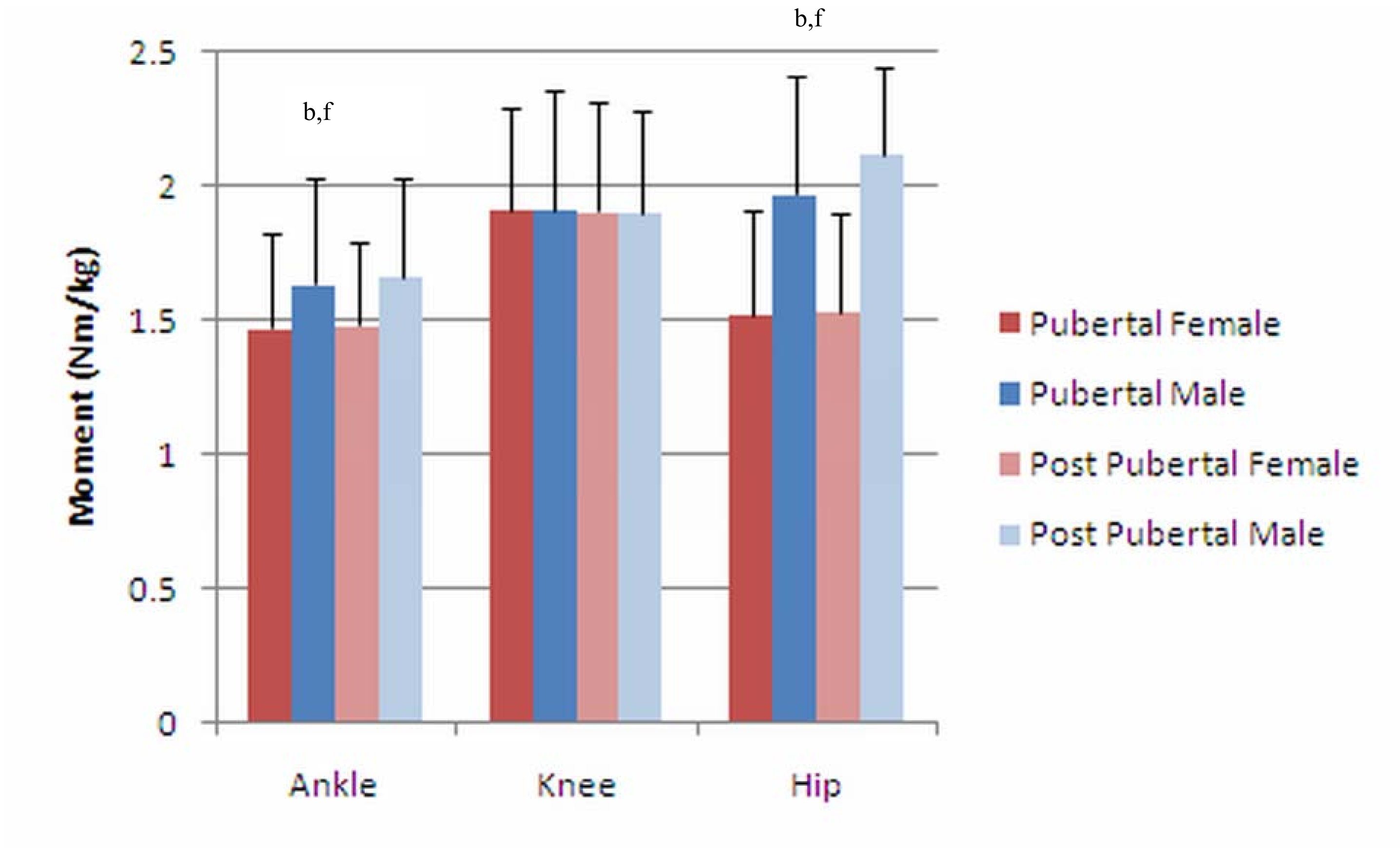


Figure 4.6. Mean (standard deviation) normalized joint moment
[b]Denotes statistically significant effect of sex ($p < 0.05$), [f]Denotes statistically significant interaction of sex and maturation ($p < 0.05$)

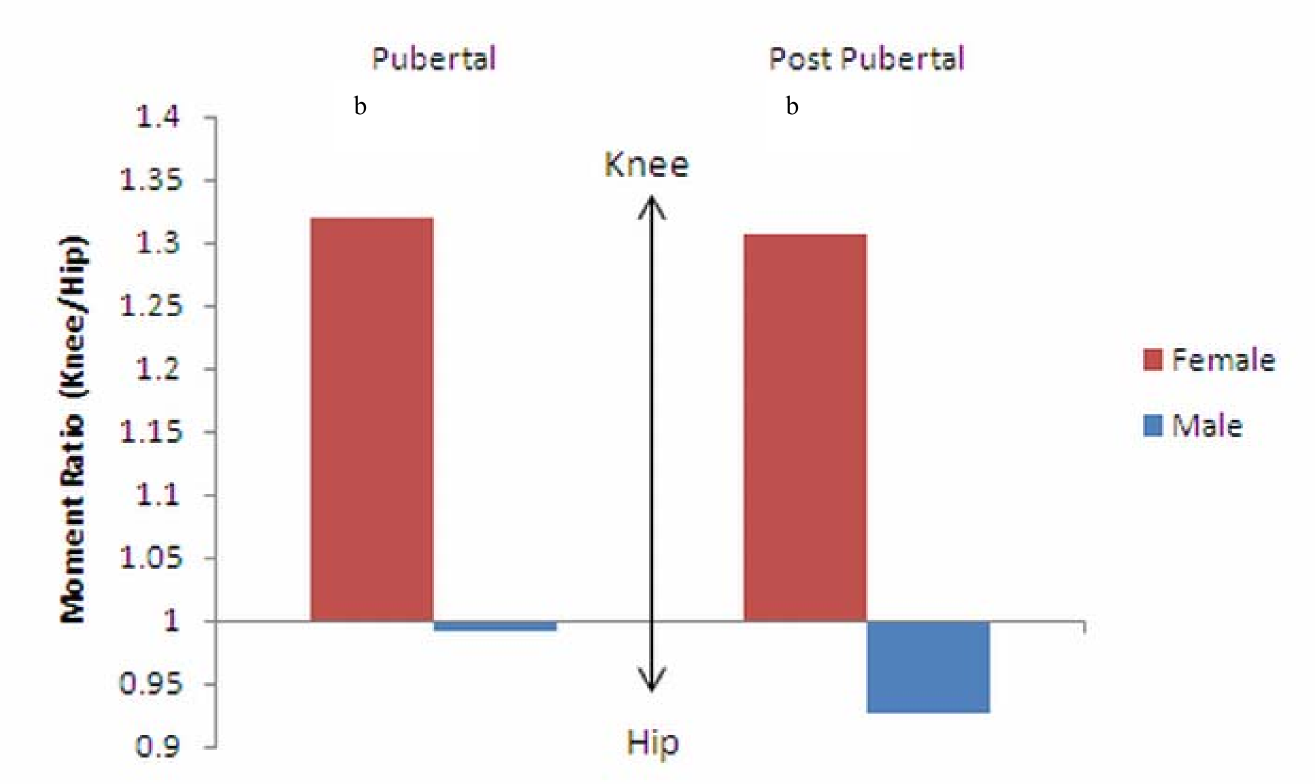


Figure 4.7. Peak external knee to peak external hip moment ratio
^{b}Denotes statistically significant effect of sex ($p < 0.05$),

Chapter 5. Absence of a Neuromuscular Performance Spurt

Introduction

Sex difference in anterior cruciate ligament (ACL) injury rates do not appear to be present in pre-pubescent athletes.[30, 31, 99] In contrast, adolescent and adult females suffer ACL injuries at a 2 to 10-fold greater rate compared to male athletes participating in the same high-risk sports.[1-6] Although the number of ACL injuries increase with age in both males and females, females have higher rates immediately following the growth spurt.[100] Insurance data show that girls and boys diverge in knee and ACL injury risk within the same time frame, after girls begin to mature (age 11 to 13).[101] In addition, data from the American Academy of Orthopaedic Surgeons indicate that the prevalence of ACL surgeries peaks in girls at age 16, when they reach full maturity.[102]

Longitudinal and cross sectional studies generally indicate that males have significantly greater increases in strength and power measures compared to females throughout adolescent growth (for summary see [44, 55]). An increase in neuromuscular measures (strength and power) during adolescent growth is operationally defined as a neuromuscular spurt.[51] Sex differences in strength and power during adolescent growth may help explain the increase of ACL injury risk in females during adolescent growth.[36] Angular measures of knee abduction increase in females during the same timing of maturation that strength and power measures increase in males.[36] The absence of a neuromuscular performance spurt in females may relate to altered movement patterns that increase risk of ACL injury.

In a longitudinal study, Quatman et al.[51] showed that pubertal males increased vertical jump height in the span of a year 7.3% while females had no significant increase. Additional longitudinal[44, 55, 156] and cross-sectional[36, 141] studies have found similar results throughout maturation. For instance, Kellis et al.[141] examined 379 basketball players and found that as age increased from 13 to 18 years the sex differences in vertical jump height also increased. Hamstrings and quadriceps peak torques at 300 °/sec were found to be greater in post-pubertal males compared to pubertal males.[36] In addition, measures of peak torque in post-pubertal males were greater than post-pubertal females.

While movement patterns may begin to differ between sexes during rapid adolescent growth, the relationship between this change and absence of a neuromuscular spurt has not been longitudinally investigated. The differences in neuromuscular performance between the genders during and following puberty may be important contributors to altered biomechanics. This could potentially explain the increased risk of ACL injury in females following puberty and may help to identify the optimal time to implement injury prevention programs.[105] The objectives of this study were to identify longitudinal neuromuscular performance differences among sex and maturational groups and secondly to investigate the relationship of altered movement patterns, joint stiffness and neuromuscular performance measures of strength and leg power. The first hypothesis was that males would show significant increases in vertical jump and strength compared to females. I also hypothesized that longitudinal increases in knee abduction moments and motion would significantly correlate with the absence of increased leg power in girls. In addition, longitudinal decreases in knee stiffness during landing would significantly correlate with the absence of increased hamstrings strength in girls.

Methods

Subjects

The same subjects described in Chapter 3 were included in this study. The subjects were classified as pubertal or post-pubertal with the modified Pubertal Maturational Observational Scale (PMOS).[41] Each subject participated in the first testing session immediately before their basketball or soccer season. Approximately one year after the initial testing session the subjects were retested using the exact same methods. Subjects were excluded from this study if they had previous history of knee or ankle surgery. The data collection procedures were approved by Cincinnati Children's Hospital Institutional Review Board. Each parent or guardian reviewed and signed the Institutional Review Board approved consent to participate form prior to data collection. Child assent was also obtained from each subject prior to study participation. The database review and data analysis was certified exempt (Protocol No. 08-0928-X4B) under the University of Kentucky's Institutional Review Board based on federal regulation 45 CFR 46.101(b) for the protection of human subjects related to the study of existing data.

Procedures

Isokinetic knee extension/flexion strength was collected with the subject seated on a dynamometer (Biodex, Shirley, NY) and their trunk perpendicular to floor, hips flexed to 90° and knees flexed to 90° (Figure 5.1). A warm-up set of 5 knee flexion/extensions was performed for each leg at 300°/sec. The test session consisted of 10 knee flexion/extension repetitions for each leg at 300°/second. Peak flexion and extension torques were recorded.

Retroreflective markers were placed on each subject and a static trial was collected as previously described (Figure 3.1).[75] Three trials of the drop vertical jump (DVJ) were collected with the subjects dropping from a 31 cm box. The subjects dropped directly down off the box and immediately perform a maximum vertical jump, raising both arms as if they were jumping for a basketball rebound.[15] A suspended ball was placed above them as a target to reach during the vertical jump. The ball height was positioned based on each subject's previously measured maximum countermovement jump (Figure 5.2).

Data trials were collected with EVaRT (Version 4, Motion Analysis Corporation, Santa Rosa, CA) using a motion analysis system with eight digital cameras (Eagle cameras, Motion Analysis Corporation, Santa Rosa, CA). The video data was collected at 240 Hz. The motion analysis system was calibrated based on manufacturer's recommendations. Two force platforms (AMTI, Watertown, MA) were embedded into the floor and positioned 8 cm apart so that each foot would contact a different platform during the stance phase of the DVJ. The force plate data were time synchronized with the motion analysis system and collected at 1200 Hz.

Data Analysis

Following data collection, 3D marker trajectories were examined for accurate marker identification within EVaRT (Version 4, Motion Analysis Corporation, Santa Rosa, CA) and exported to a C3D file format. The C3D files were then further analyzed in Visual3d (Version 4.0, C-Motion, Inc., Germantown, MD). The procedures within Visual3D were described in detail previously (Chapter 3, Chapter 4). Sagittal plane ankle, knee and hip angle and moments were used to calculate joint stiffness parameters.[54, 119] Joint stiffness was modeled based on a rotational spring for each joint. Rotational spring plots (joint moment as a function of joint angle) were calculated for each trial within MATLAB.[54, 149] Stiffness was calculated as the slope of the moment-angle curve from a least squares linear regression during the stance phase. Maximum knee abduction angle and moment were calculated (Chapter 3) during the landing portion of the DVJ.

Vertical jump height was calculated from the DVJ trials based on the vertical trajectory of the greater trochanter reflective marker.[51] The difference between the maximum height and standing height was calculated as maximum vertical jump height. Figure 5.4 shows a related calculation with estimated center of mass during DVJ.

The difference (Δ) between consecutive testing years was calculated of the variables described above (vertical jump, isokinetic torque, active joint stiffness, knee abduction moment and angle) and used in the analysis.

$$\Delta = test_2 - test_1$$

Statistical Analysis

Two between group independent variables of sex (female, male) and maturation level (pubertal, post-pubertal), in addition to the within subject independent variable (repeated measure) of two consecutive year screening sessions, were used in the statistical design. The dependent variables were vertical jump height, knee extension and flexion peak torque at 300 °/sec. A 2X2X2 ANOVA (maturation, sex, session) was used to test each hypothesis. Pearson correlation coefficients were calculated to identify if changes in the dependent variables related to change in the dependent variables from chapters 3 & 4. An $\alpha \leq 0.05$ was used to indicate statistical significance. Analyses were conducted using SPSS v16.0 (SPSS Inc., Chicago, IL).

Results

Vertical Jump

Males had a significantly greater increase in vertical jump from the first to second year of testing compared to females (Figure 5.4, sex * session interaction, $p = 0.006$). Females increased their vertical jump by 4.2%(± 8.7). Males nearly doubled the yearly increase, in comparison to females, with a vertical jump height change of 8.2% (±8.3) ($p = 0.003$). Pubertal athletes also showed greater yearly increases in vertical jump height compared to post-pubertal (maturation * session interaction, $p = 0.001$). As expected, the post-pubertal males had a higher vertical jump height compared to other groups (Figure 5.4, sex * maturation interaction, $p = 0.005$).

Isokinetic Quadriceps and Hamstrings Strength

Both male and female pubertal athletes had increases in normalized peak quadriceps torque at 300 °/sec (maturation * session interaction, $p = 0.016$). Yearly quadriceps strength changes were not found in post-pubertal subjects (Figure 5.5). Post-pubertal males had greater normalized quadriceps strength compared to other groups (Figure 5.5, sex * maturation interaction, $p < 0.001$).

There were no differences between testing years with normalized hamstrings peak torque ($p > 0.05$). However, males overall exhibited greater hamstrings peak torque at 300 °/sec compared to females (Figure 5.6, sex main effect, $p < 0.001$).

Correlated Variables

Changes across testing years of the dependent variables presented in Chapters 3-5 were calculated. The primary variables of interest were knee abduction angle and moment, active joint stiffness, vertical jump height and hamstrings strength. Changes in active joint stiffness variables were significantly correlated to vertical jump height change in all the athletes combined (ankle r = 0.13, knee r = 0.12, hip r = 0.13; $p < 0.05$; Figure 5.7). Hamstrings peak torque was not related to stiffness or knee abduction changes ($p > 0.05$) in all the athletes combined. However, in post-pubertal athletes, increased hamstrings peak torque was significantly correlated to increased hip stiffness (r = 0.18, $p < 0.05$). Vertical jump height was correlated to knee abduction motion (r = -0.11, $p < 0.05$) and moment (r = -0.14, $p < 0.05$), which indicated that as vertical jump height increased, the knee abduction measures increased (became more negative).

Knee abduction angle significantly correlated to knee (r = 0.17, $p < 0.01$) and hip stiffness (r = 0.16, $p < 0.01$). Interestingly, in females, increased knee stiffness (r = 0.21, $p = 0.001$) significantly correlated to decreased knee abduction angle (Figure 5.8). Hip stiffness changes were not related in females to changes in knee abduction angle ($p > 0.05$). However, increased hip stiffness was related to decreased knee abduction angle (r = 0.35, $p = 0.01$) in male subjects (Figure 5.9). Increased stature was significantly related to increased knee abduction moment (r = -0.15, $p = 0.02$) in female but not male athletes.

Discussion

The first purpose of this study was to identify longitudinal neuromuscular performance differences among sex and maturational groups. We supported our first hypothesis that males would demonstrate a significant increase in vertical jump height compared to females. Beunen et al.[156] reviewed the literature relevant to sex and maturational differences in motor performance and suggested that boys had a "power spurt" in vertical jumping. The performance in girls matched boys up to about 13 years and then had little improvement.[156] Others have shown similar differences during maturation when comparing vertical jump height between sexes. Kellis et al.[141] tested four different types of vertical jump performance in a cohort of male and female basketball players. They compared the vertical jump height to age and sex and found that males had significant increases in performance compared to females.[141] While the statistical results are similar, the overall jump heights appear to be slightly lower in the Kellis et al. study compared to the present findings. The difference is likely the result of the higher box height (40.0 cm) compared to the box height in our study (31.0 cm). For example, if we compare the 13 year old group[141] to the second year of testing in the pubertal females (average age 13 years old), the DVJ performance was 25.6 ± 3.6 cm compared 32.0 ± 4.3 cm, respectively. In addition, differences in technique could also factor into the differences in absolute jump height as we used an overhead target and allowed arm swing which increase vertical jump performance.[50, 157]

Both male and female pubertal athletes increased quadriceps strength during the span of a year of rapid pubertal growth. Interestingly, no increases were found in hamstrings strength. However, males exhibited larger hamstrings strength overall compared to females. The lower overall hamstrings strength in females may be related to increased risk of ACL injury. A previous study showed that female athletes, prior to suffering an ACL injury, had decreased hamstrings strength compared to males.[158] However, female athletes who did not go on to ACL injury had similar hamstrings strength compared to matched male athletes.[158] Decreased hamstrings strength has been implicated as a potential mechanism related to lower extremity injuries and potentially ACL injury risk in female athletes.[159] Joint stabilization can be accomplished through hamstrings and quadriceps co-contraction and may be necessary when the joint is subjected to high quadriceps activation or when the passive structures are compromised.[160, 161] Withrow et al. reported that increased hamstrings force during the flexion phase of simulated landings decreased relative strain on the ACL.[162] Muscular strength, as well as the joint position in which the muscle groups are activated, are important concepts related to joint stabilization.[152] Males had significantly greater hip flexion than females at initial contact (Chapter 4) which theoretically would increase the activation of the hamstrings compared to an initial joint posture that is more extended, which would place the trunk and body center of mass in a more posterior position.[153]

The functional significance of the hamstrings and quadriceps strength measurements is limited based on the isokinetic speed and joint positions. The current protocol collected isokinetic strength at a relatively high speed of 300 °/sec. Concentric muscle action was measured for both the hamstrings and quadriceps muscles. The difference in muscle action (concentric and eccentric) during an open kinetic chain test may also limit the relationship of the strength results to a closed kinetic chain landing exercise.

The second aim of this chapter was to relate the changes in performance variables to abduction motion and active joint stiffness. The strength of the relationship among all the variables was low. Even with this limitation, there were several significant correlations that were of interest. For example, we suggested in **Error! Reference source not found.** that active joint stiffness may be used to control knee abduction motion. There was a significant relationship between increased stiffness and decreased knee abduction. This indicates that as athletes matured between the two testing years, those that increased active joint stiffness at the knee and hip also had a tendency to reduce peak knee abduction angle. When the relationship between stiffness and altered movement was examined within males, increased hip stiffness appeared to be related. Whereas in females, hip stiffness was not significantly related to altered knee abduction. Males appear to utilize a different strategy during growth and development to control knee abduction based on increased hip stiffness. This relationship is strengthened by the results in Chapter 3 and Chapter 4, that show lower knee abduction motion and moments with greater hip extensor moment and hip stiffness, in males compared to females. It is important to consider that it is not appropriate to imply causation from these results. While there were significant correlations, the relationships could be coincidental and could be related to other growth and developmental factors. A randomized controlled trial with an intervention to increase active joint stiffness would be recommended to identify the casual relationship to knee abduction.

Neuromuscular training programs have been successful at reducing knee abduction motion and moments.[11, 142, 143, 163] A comprehensive review of ACL injury prevention programs indicates that neuromuscular training appears to decrease ACL injury rates in female athletes.[24] These programs typically incorporate plyometric training and technique analysis. Plyometric exercises, such as DVJ, focus on the body's ability to effectively use the stretch-shortening cycle (SSC). SSC is defined as a muscle stretch prior to a rapid shortening to accelerate the body or a limb.[164] The SSC muscle action increases power and performance when compared to pure concentric actions.[165-167] Jumping is more powerful if an athlete initiates the movement with a countermovement or preparatory descent prior to the leap.[166] These types of exercise may help prepare an athlete for demanding multidirectional sport maneuvers, by controlling the external forces and limiting potentially dangerous joint postures. In addition to changes with knee abduction, plyometric training has also been shown to positively alter hip kinematics and kinetics.[168] Lehpart et al.[168] found increased hip flexion at initial contact and increased peak external hip flexion moment following a plyometric training protocol. They suggested that the modifications at the hip likely increase the hamstrings forces that protect the ACL.[168] Hip posture may play an important role in the mechanical efficiency of hamstrings in relation to quadriceps.[152] In Chapter 4 we identified that females landed with less hip flexion at initial contact in addition to lower hip stiffness and hip flexion moment compared to males. Focused hip training that incorporates plyometric activities with technique feedback may be warranted in young female athletes prior to the development of these differences between sexes.

Decreased hip strength (gluteus medius and gluteus maximus), measured from a hand-held dynamometer, has been previously related to greater knee abduction at initial contact and peak during landing.[169] We did not measure hip strength in the current study, but further investigation is warranted. In addition, hip abduction motion and strength may also play an important role in joint stabilization. Jacobs et al. evaluated isometric hip abduction peak torque and found that females demonstrated a relationship between decreased hip strength and increased knee abduction displacement and hip adduction during landing.[81]

Conclusions

Males had a significantly greater yearly increase in vertical jump height compared to females. Increased vertical jump height correlated with increased active joint stiffness. Quadriceps strength increased in both sexes while hamstrings strength did not change in females. Males exhibited greater strength in both the quadriceps and hamstrings muscle groups when compared to females. Post-pubertal athletes demonstrated a significant correlation between increased hamstrings peak torque and increased hip stiffness. These findings indicate that hamstrings focused training that increases isokinetic hamstrings strength may also increase active hip joint stiffness during a DVJ. Contrasting results between sexes were found to relate to the decreased knee abduction angle from the first year of testing to the second. Males showed a significant relationship between increased hip stiffness, while females had a significant relationship with knee stiffness, to decreased knee abduction angle. Focused hip training that incorporates plyometric activities with technique feedback may be warranted in young female athletes to address sex differences in development of ACL injury risk factors as they mature.

Figure 5.1. Isokinetic knee flexion and extension trials at 300 °/sec.

Figure 5.2. MX-1 vertical jump test with a countermovement jump.

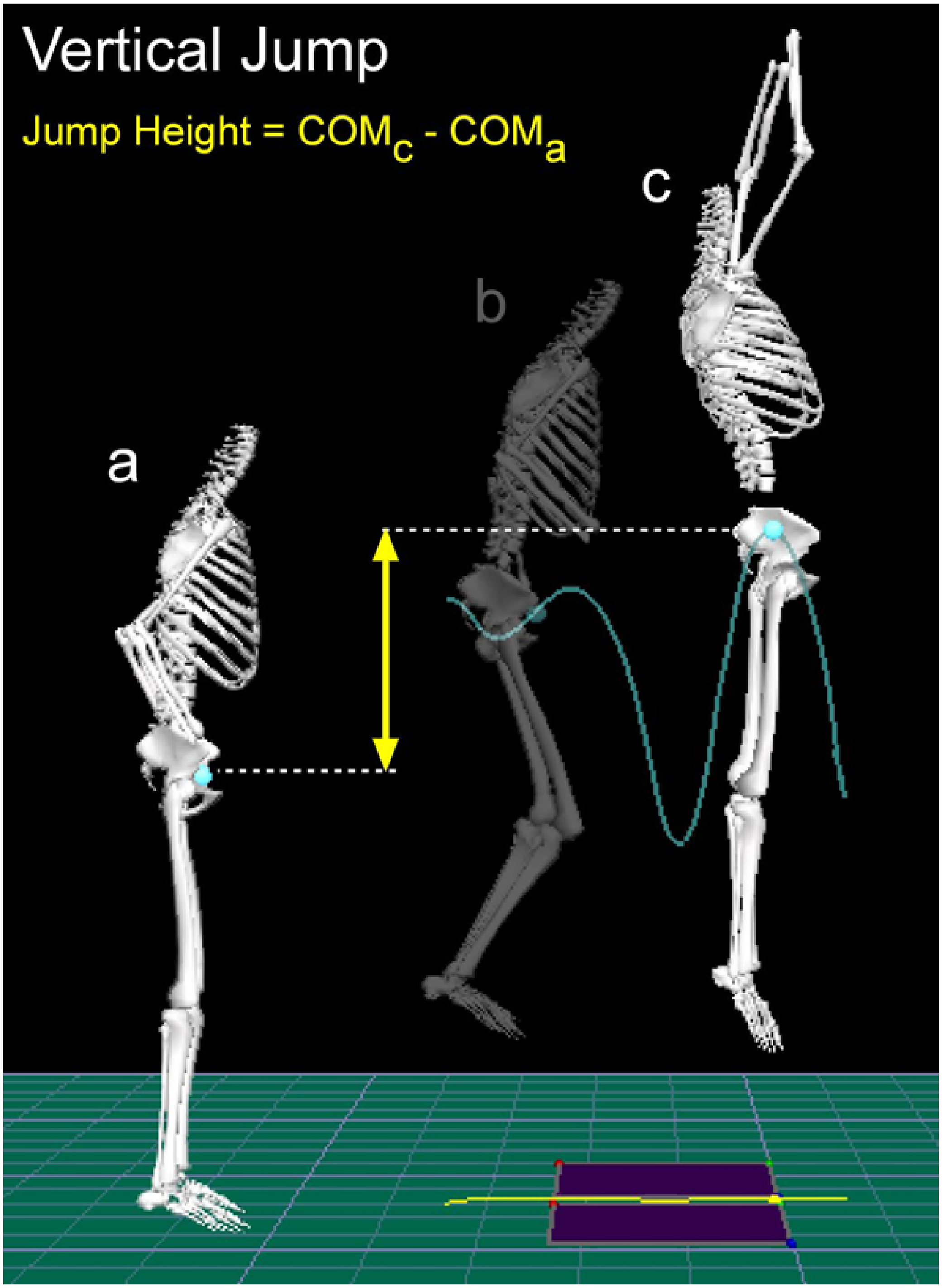


Figure 5.3. Calculation of vertical jump based on vertical trajectory of the body center of mass estimated from the motion analysis system.

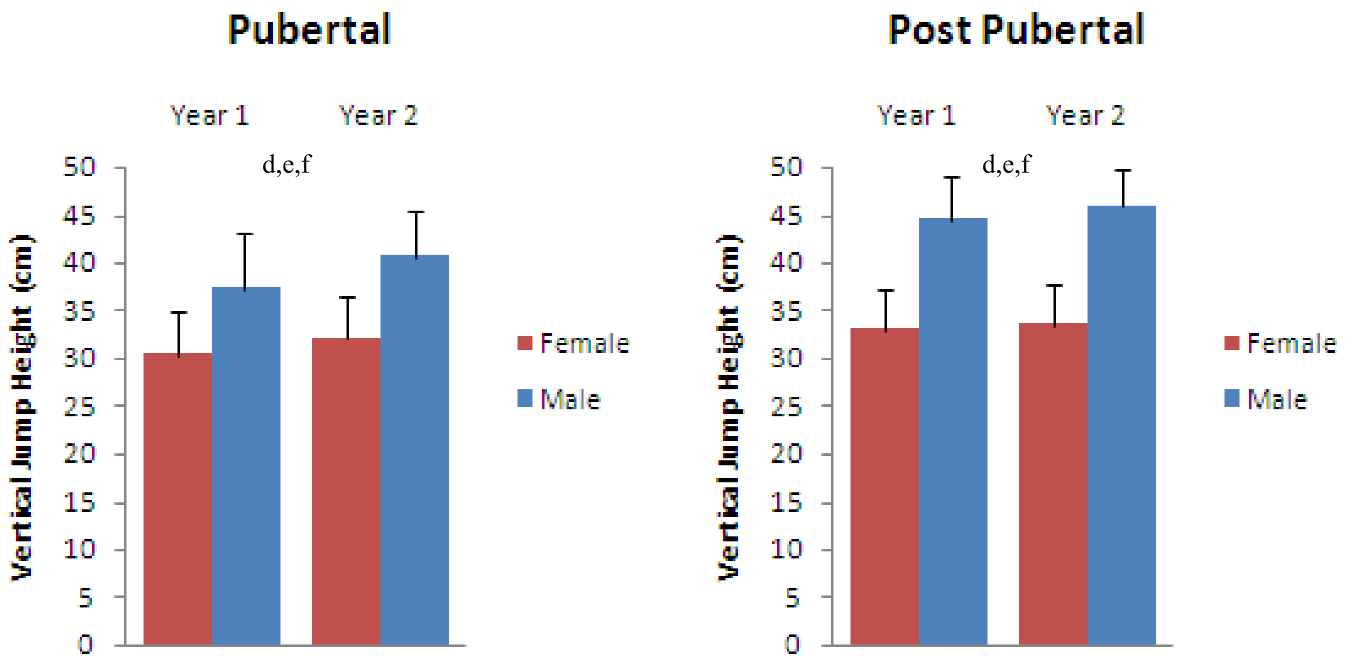


Figure 5.4. Calculated jump height from DVJ (mean and standard deviation)
[d]Denotes statistically significant interaction of year and maturation ($p < 0.05$), [e]Denotes statistically significant interaction of year and sex ($p < 0.05$), [f]Denotes statistically significant interaction of sex and maturation ($p < 0.05$)

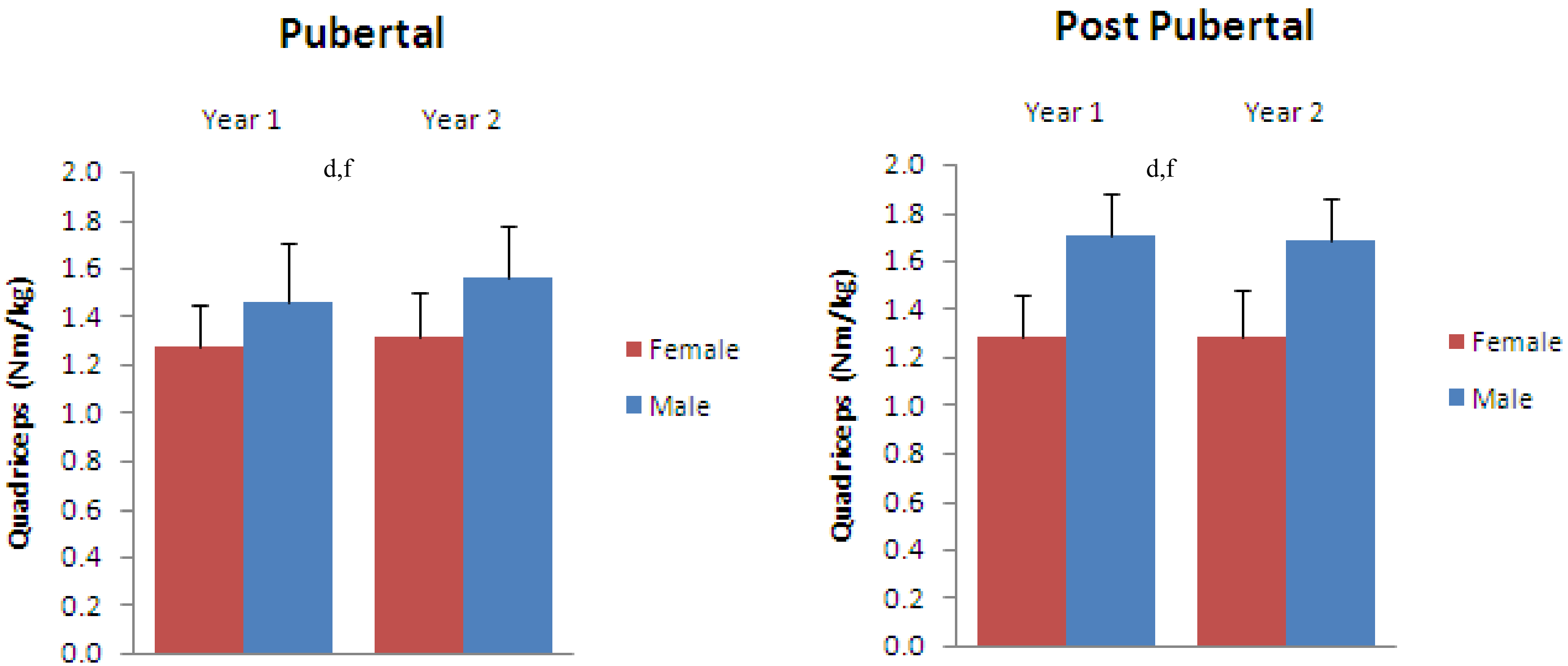


Figure 5.5. Normalized isokinetic quadriceps peak torque (mean and standard deviation)
[d]Denotes statistically significant interaction of year and maturation ($p < 0.05$), [f]Denotes statistically significant interaction of sex and maturation ($p < 0.05$)

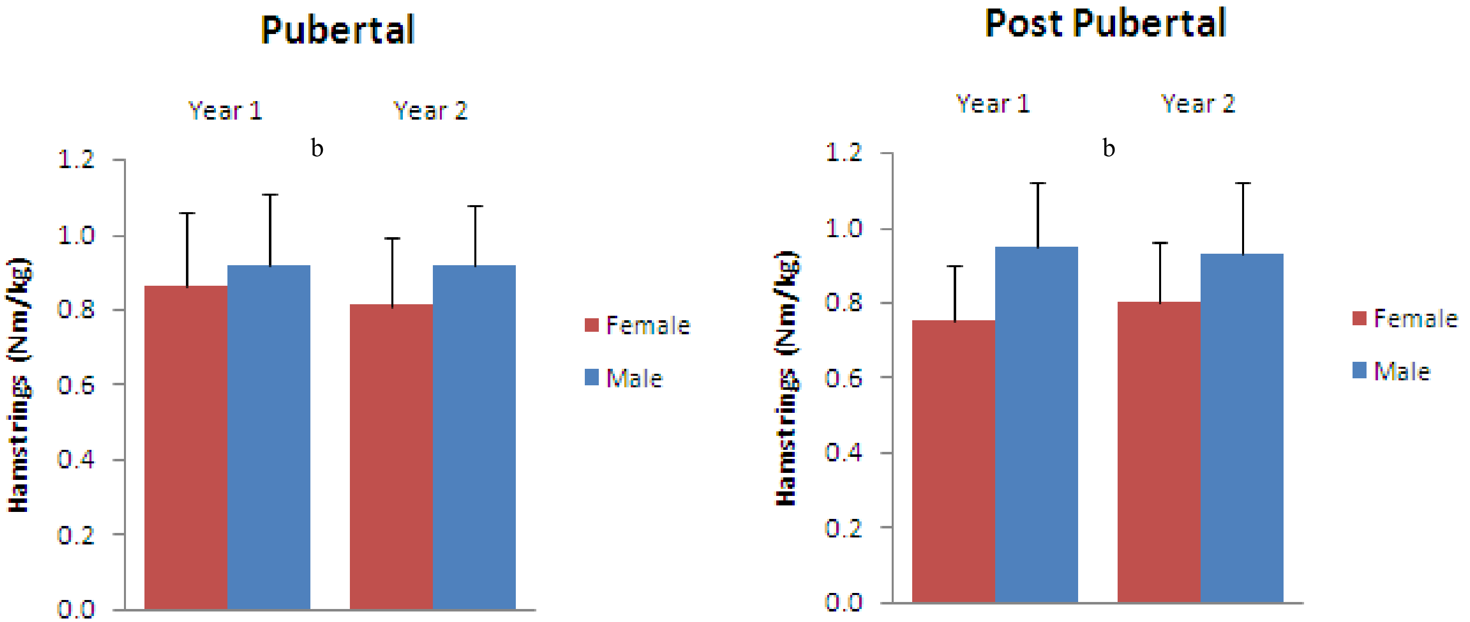


Figure 5.6. Normalized isokinetic hamstrings peak torque (mean and standard deviation)
^{b}Denotes statistically significant effect of sex ($p < 0.05$)

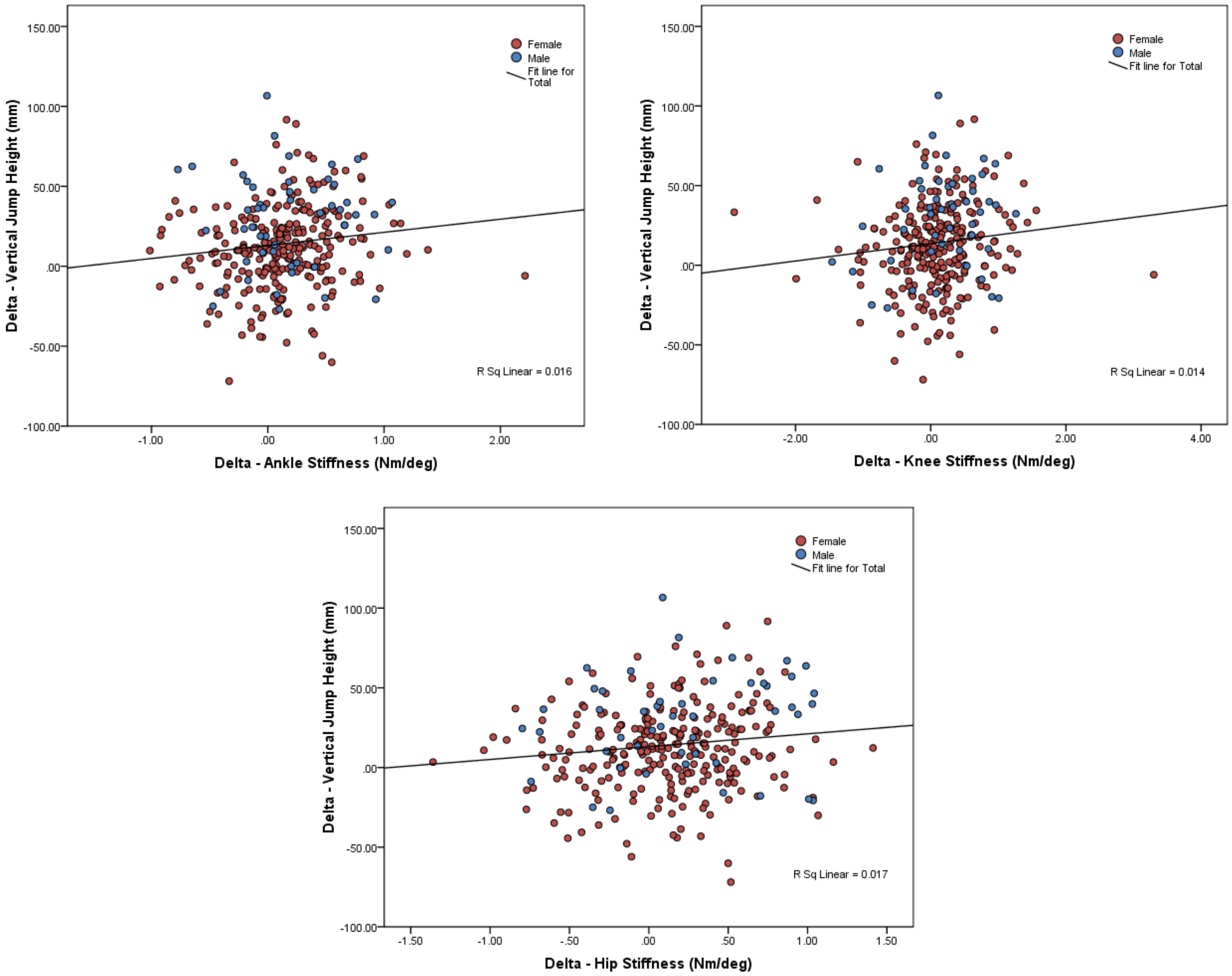


Figure 5.7. Scatterplot of yearly changes in vertical jump height and ankle (top left), knee (top right) and hip (bottom) stiffness

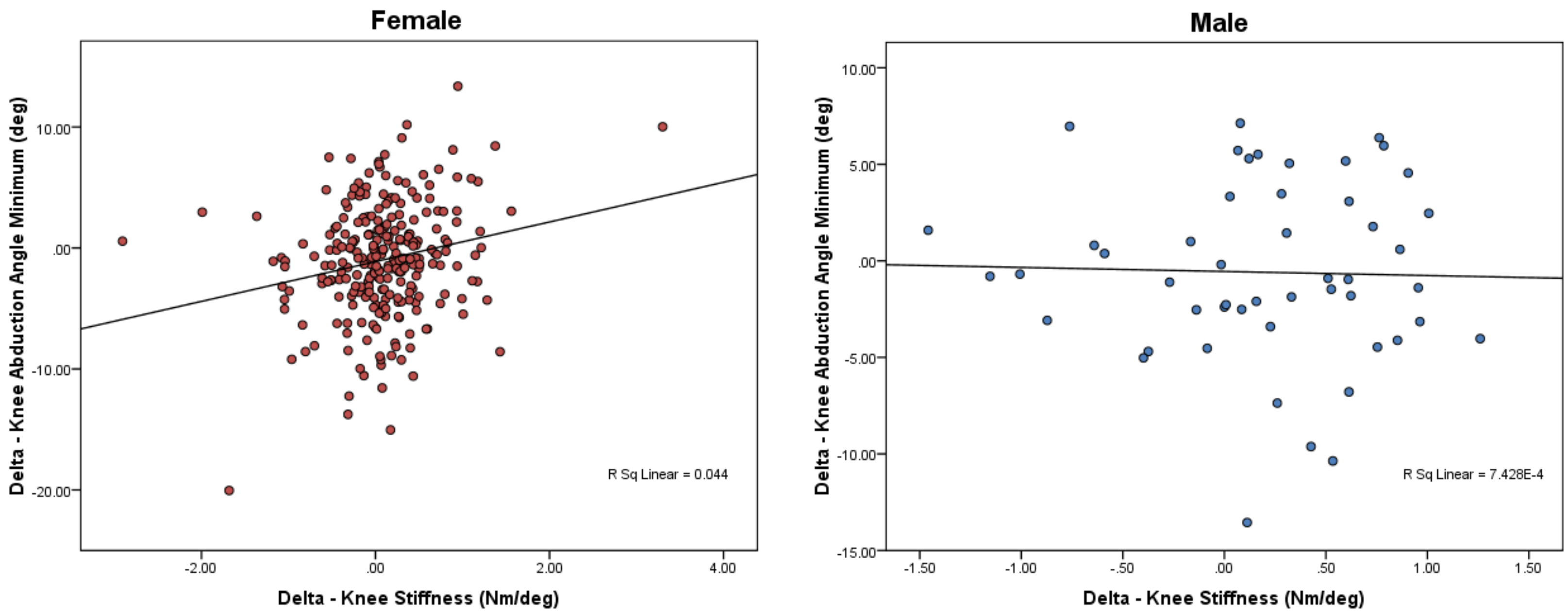


Figure 5.8. Female (left) and male (right) scatterplot of yearly changes in knee abduction angle and knee stiffness

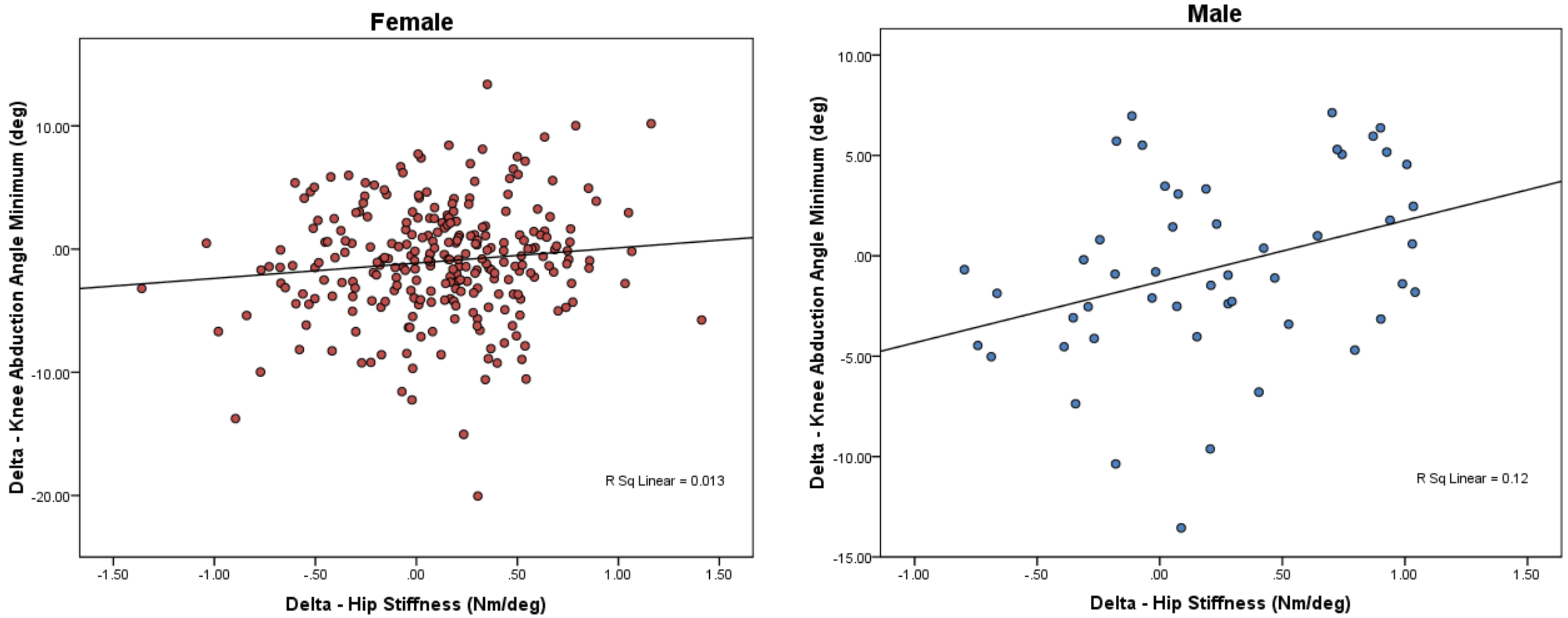


Figure 5.9. Female (left) and male (right) scatterplot of yearly changes in knee abduction angle and hip stiffness

Chapter 6. Conclusions

Summary of Results

The overall purpose of this dissertation was to determine if neuromuscular ACL injury risk factors in female athletes increase following rapid growth and development compared to males. The first research questions were addressed in Chapter 3 and Chapter 4. Specifically, I asked if the onset of neuromuscular risk factors in female athletes occur during rapid adolescent growth. Male and female athletes were tested over two consecutive years to determine if risk factors associated with ACL injury increased. Pubertal females showed a significant longitudinal increase in knee abduction angle compared to post-pubertal females and both male groups. The increase in knee abduction angle appeared to remain consistent, as the post pubertal female cohort had greater overall knee abduction compared to post-pubertal males. Similar results were found with a greater magnitude of knee abduction moment in post-pubertal females compared to males.

Active joint stiffness was investigated as a potential risk factor that may be related to increased risk of ACL injury. Throughout maturation, males were hypothesized to develop increased active joint stiffness, which may help control frontal plane lower extremity motion. We found that males and females increased ankle, knee and hip active stiffness from the first to second year of testing. Ankle and hip stiffness was increased significantly more in the pubertal group compared to post-pubertal. However, when active joint stiffness was normalized to body mass, there were no significant differences between the testing years. Sex and maturational group differences were found in hip and ankle joint stiffness. Post-pubertal males had significantly greater hip stiffness than the other groups (even when normalized to body mass). This indicates that post-pubertal males landed with a different neuromuscular strategy. Males preferred to utilize external hip flexion moment, as opposed to the knee flexion moment, as well as landing at initial contact with greater hip flexion, compared to females. The theoretical concept of a knee extensor dominant landing strategy in females compared to a hip extensor dominant strategy in males should be further explored.

The second question that this dissertation addressed was the relationship between neuromuscular performance variables and purported risk factors. We first identified if a "neuromuscular spurt" was apparent in males, but not females. This hypothesis was supported, as males had a significantly greater increase from year to year in vertical jump height compared to females. Vertical jump height is often related to a measure of whole body power. Quadriceps strength increased in both sexes while hamstrings strength did not change. Males exhibited overall greater strength in both the quadriceps and hamstrings muscle groups when compared to females. The change from year to year was calculated for each of the variables of interest and correlated. Significant correlations were found in a few of the variables; however, they were relatively low in strength. An interesting correlation between hip stiffness and decreased knee abduction angle was found in males. This indicates that during a year of adolescent growth and development, males increased hip stiffness and decreased knee abduction angle. In contrast, females appeared to use a knee stiffness strategy as this was significantly correlated in females, but not males, to decreased knee abduction angle. Further interpretation would indicate that females that did not increase knee stiffness during a year of adolescent growth had increased knee abduction angle.

Practical Implications

Neuromuscular training programs have been successful at reducing knee abduction motion and moments.[11, 142, 143, 163] A comprehensive review of ACL injury prevention programs indicates that neuromuscular training appears to decrease ACL injury rates in female athletes.[24] These programs typically incorporate plyometric training and technique analysis. Studies are ongoing that show that knee abduction measures may be useful at identifying those females that are at increased risk of ACL injury.[27] We have shown in this study that pubertal females have increased knee abduction motion during a year of adolescent growth. Early puberty may be an appropriate time during maturation to institute an intervention program which aims to control knee abduction motion and torque as well to induce a neuromuscular spurt through focused hip extensor strength training. The pubertal female group in our study was approximately 12 years old and estimated to be at 88 percent of adult stature. Therefore, training programs may be most beneficial prior to peak height velocity, which occurs near 92 percent of adult stature, and represents the largest rate of growth during adolescence.

Recommendations for Future Research

A limitation in our study was that group differences between pubertal groups were cross-sectional in nature, as we did not follow the subjects through pubertal and postpubertal stages of development. Follow-up studies should be considered which follow individuals in a longitudinal nature throughout adolescent development. Accurate and practical screening and identification of athletes at increased risk of ACL should be considered. Simpler methods have been investigated and could be used to collect valuable screening information on large cohorts of athletes. Two-dimensional frontal plane knee motion or angular displacement may prove valuable to include in standardized pre-participation physicals.[15, 170, 171] It is likely that a large number of the female sports population would demonstrate decreased dynamic knee stability and require intervention. The utility of a screening and intervention program should be investigated with the highest level of evidence research design (randomized controlled trial). Reduction of female injury rates would potentially allow thousands of females annually to continue the health benefits of sports participation and avoid the long-term complications of osteoarthritis, which occurs with a 10 to 100-fold greater incidence in ACL-injured than in uninjured athletes.[39, 40]

APPENDICES

Appendix A. The effects of age and skill level on knee musculature co-contraction during functional activities: A systematic review[172]

Kevin R. Ford, Antonie J. van den Bogert, Gregory D. Myer, Robert Shapiro and Timothy E. Hewett

Introduction

The development of sports related skills requires a complex coordination between the agonistic and antagonistic muscles at a joint to maximize the degrees of freedom and force output with the required dynamic restraints to maintain required local joint stability.[173] During maturation and skill development, inhibition of antagonist muscle groups is thought to be progressively learned until an efficient movement pattern is obtained.[117] A classic motor learning theory contends that excessive antagonistic contribution during dynamic tasks may decreases the system's "degrees of freedom" during initial acquisition of a new skill.[173-175] Accordingly, the degrees of freedom are gradually increased and optimized in order to execute the task in the most efficient manner in the skilled performer.[174, 175] Prior investigations have evaluated this relationship between agonist and antagonistic muscles systems in attempts to define optimal motor control and learning patterns in numerous types of movements in various populations.[147, 173, 176]

Muscular co-contraction is operationally defined as activation of both the agonist and antagonist muscle groups crossing the same joint.[116] Mechanically, increased activation levels of the antagonist muscle group results in a higher joint stiffness, reduced agonist force output and reduced net joint moment.[116] During activities that require maximum performance (e.g. push off phase of a jump) or throughout the entire stretch shortening cycle, inhibition of antagonist muscles would often be considered an efficient adaptation. If antagonist muscle forces increase, more work is required and decreased efficiency results for any given movement. Thus when applying the theoretical model of motor performance, without consideration of the joint stability required to maintain the integrity of the joint, decreased co-contraction would be directly related to increased power output at a joint.

However, during dynamic human movement co-contraction is a potential motor control strategy used to dynamically stabilize and protect a joint. Joint stability through co-contraction may be necessary when the joint experiences high distraction or shear forces and/or when the passive structures are compromised. For example, hamstrings activation can decrease the load on the passive restraints of the knee,[177] increase the knee joint compression force and stabilize the knee from external varus/valgus load.[70] A panel of experts suggests that female athletes, who are at a higher risk of ACL injury than males,[4] should focus on hamstrings strengthening exercises[35] and appropriate dynamic co-contraction (without limiting joint motion). Increased strength and recruitment of the hamstrings musculature may help to decrease the coronal plane rotations and anterior shear forces on the ACL.[70] Female athletes exhibit increased coronal plane motion and moments during a variety of athletic maneuvers compared to males.[15, 17, 75, 82, 108, 123] Decreased ability to control external coronal plane loads may be the symptom of decreased ability to recruit the hamstrings musculature, especially in response to increased quadriceps strength at high velocities.[178] Decreased co-contraction and dynamic stabilization of the knee joint in response to excessive coronal plane loads may underlie the increased risk of ACL injury in female athletes.[27]

Co-contraction levels are high during normal dynamic joint loading movements such as landing.[179] Considering that there is a potential conflict between joint stability and movement efficiency, important insights may be gained by comparing co-contraction levels among various movement tasks in relation to the mechanistic effects of age and skill development. The purpose of the current report was to critically review the current literature relating the effects of age and skill level on motor control patterns of knee musculature co-contraction during functional movements.

Methods

A search of electronic databases, MEDLINE (1966 – October 2006) and CINAHL (1982 – June 2007), was performed with the search terms specifying co-contraction (cocontract*, co-contract*, coactive* or co-activ*). The search was focused on the effects age and/or skill level and were limited by the keywords of age or skill level (skill*) or experience (experi*). Articles were included in the review if they were a randomized controlled trial or cohort study and investigated co-contraction (index or ratio) with electromyographical analyses during functional activity. Articles were excluded that did not perform investigations on normal or athletic population (i.e. osteoarthritis and elderly). Abstracts and unpublished studies were also excluded.

Results

Six articles[139, 147, 180-183] were identified that presented knee muscular co-contraction patterns in relation to age or skill level. Each article is briefly described below by publication date (Table B.1). Interpretations and possible limitations of each study are presented in detail in the discussion.

Frost et al [181]

The stated purpose of this study was to assess co-contraction of three different age groups of children during walking and jogging and to compare the magnitude of co-contraction among them. The investigation evaluated a total of 30 total healthy, active subjects with ten subjects in each age group (7-8 yrs, 10-12 yrs and 15-16 yrs). Five different treadmill speeds (2 walking and 3 jogging) were used for each age group, with one walking and 2 jogging speeds in common between adjacent age groups. Surface electromyography (EMG) electrodes (Ag/AgCl) were placed on the vastus lateralis and "middle of the hamstrings group" (no specific muscle was identified in the paper) with an inter-electrode distance of 4cm. Raw EMG was first normalized to the maximum value obtained during either the treadmill trials or maximum voluntary contraction (MVC) trials. A co-contraction index, dimensionless value, was calculated based on overlaying the linear envelopes of the vastus lateralis and hamstrings, calculating the area of overlap and dividing by the number of data points. Frost et al.[181] found when comparing the running speeds at the same relative metabolic intensity (% $VO_{2\ max}$) the co-contraction index was higher in younger compared to older aged groups. They concluded that co-contraction was an important component of age-related differences in VO_2 which was used to possibly enhance joint stability at the younger age.

Croce et al.[139]

This study examined the differences between pre-pubescent and post-pubescent male and female subjects. The authors stated that different stabilization patterns might be a causative factor related to ACL injuries. Two groups of subjects were studied based on age and were classified as pre-pubescent (7-10 year old females, and 8-11 year old males) or post-pubescent (19-29 year old male and female). A two foot, vertical jump (50% of maximum) and landing was analyzed with the subject landing with the dominant foot on a force platform. EMG surface electrodes (Ag/AgCl pre-gelled) were placed on the biceps femoris, semimembranosus/semitendinosus and vastus medialis. The electrodes were located 2.5cm apart, parallel to the muscle fibers and over the midline between the motor end plate and tendon. The data from the hamstrings muscle sites were averaged. Mean amplitude root mean square (RMS) was calculated at three different time intervals during the trials (100 ms prior to contact, 100 ms after contact and from contact to maximum knee flexion). The EMG signal was normalized to the highest signal during the landing phase of each trial. Co-contraction ratio was calculated by dividing hamstrings by quadriceps EMG activity. Co-contraction ratio was higher in the post-pubescent subjects prior to landing, however, after landing the co-contraction ratio was higher in pre-pubescent subjects. No gender differences were found in co-contraction during the vertical jump. The authors concluded that post-pubescent subjects rely more on hamstrings activation prior to landing (pre-activation) while prepubescent subjects rely more on hamstrings activation during landing (reflexive activation pattern). This would seem to relate to a motor learning strategy throughout skill development of pre-activation to stabilize the joint prior to high ground reaction forces and joint load which exist during landing.

Hamstra-Wright et al. [147]

The purposes of this study were to assess dynamic neuromuscular restraint differences between high and low-skilled prepubescent children and to determine the contributions of sport experience and physical characteristics to motor skill. They hypothesized that high skilled and male subjects would have greater co-contraction (hamstrings and quadriceps) than low skilled and female subjects. Thirty-six prepubescent children were enrolled in this study (19 female and 17 male). High skill and low skill subjects were determined based on performance of battery of 12 fundamental motor skills on the Test of Gross Motor Development, 2nd edition (TGMD-2). Subjects above the overall mean were classified as high skill, while subjects below the mean were classified as low skill. Surface EMG electrodes (bipolar Ag/AgCl) were placed on the vastus medialis and medial hamstring. EMG was normalized to the highest activity during each trial (150ms prior to ground contract through 250 ms after). Preparatory co-contraction was determined as the medial hamstring area divided by vastus medialis area 150ms prior to ground contact during a drop jump (24cm). Vertical leg stiffness was also determined during the drop jumps based on a simple spring-mass model from the vertical ground reaction force measures. Low-skilled subjects had significantly greater (48%) preparatory co-contraction during the drop jump compared to high-skilled subjects. No differences were found in vertical leg stiffness between skill or gender groups. The authors conclude based on the higher co-contraction in low-skilled subjects, in addition to the absence of gender differences, that skill level affects neuromuscular control. They further suggest that females may develop risk factors which predispose them to knee injuries between pre- and post-puberty. The authors state that this was an “unrefined motor skill” which may compromise knee joint stability. This conclusion is directly in contrast to the study hypothesis that high-skilled athletes would exhibit greater preparatory co-contraction.

da Fonseca et al.[180]

This study compared muscular co-contraction levels during walking and landing from a jump (30cm) among male and female athletic and sedentary subjects. They hypothesized that females (athletic and sedentary) would have lower co-contraction levels than males. The hypothesis was based on both the higher ACL injury rates in females and the possible joint protective mechanism that co-contraction may have due to increased joint stiffness. Nine subjects in each group participated wtih their activity level classified based on the Cincinnati Knee Rating Scale (Level I, participate in sports activities 4-7 days a week; Level IV, do not participate in any sports activities). Surface EMG electrodes (bipolar Ag/AgCl) were placed over the vastus lateralis and biceps femoris with co-contraction index calculated similar to Frost et al.[181] during both walking and landing from a jump. EMG was filtered with a bandpass filter (10 and 500 Hz) and normalized to MVC collected from a dynamometer. Co-contraction index was only calculated for the 150ms time period prior to initial contact. There were no differences in preparatory co-contraction index during landing movements between genders or activity levels. However, during walking the sedentary females had higher co-contraction levels compared to athletic females. The authors suggest that sedentary women may compensate for weakness with higher co-contraction levels to generate appropriate joint stability.

Sigward and Powers[182]

Sigward and Powers[182] evaluated the effect of soccer experience on knee kinematics, kinetics and muscle activation patterns during side step cuts. One hypothesis of this study was that novice female athletes would exhibit increased quadriceps activation and decreased hamstring activation. Thirty young female athletes (14 – 16 years old) were classified as experienced (N=15) or novice (N=15) based on years of experience playing soccer. Surface EMG electrodes were placed on the vastus lateralis, biceps femoris and semimembranousus. EMG was filtered with a band pass Butterworth filter (20-500Hz) and a 60 Hz notch filter. The data were processed with a RMS smoothing (75ms window) and normalized to maximum voluntary isometric contraction collected prior to the cutting trials. Co-contraction was calculated, based on Besier et al.[184], by dividing the average hamstring activation by the average quadriceps activation during the initial 20% of the cutting maneuver stance phase (early deceleration). Knee joint kinematics and kinetics were also assessed during the same period. During early deceleration the novice athletes had a significantly larger co-contraction index than the experienced athletes. However, the internal knee flexor moment was significantly increased in the experienced athletes compared to the novice athletes. There was also a negative correlation (R = -0.32) between years of experience and co-contraction ratio. The authors conclude that with experience, the side-step cutting (kinetics and muscle co-contraction) task is performed in a more at-risk pattern for a non-contact knee injury. The relationship between skill acquisition (increased co-contraction) and potential at-risk patterns (decreased co-contraction) is difficult to address in one study and should be investigated in conjunction with neuromuscular training programs.

Russell et al. [183]

In a follow-up study to the previously reviewed, Russel et al.[139] evaluated knee muscular activation differences in children and adults (male and female) during landing from a normal and perturbed vertical jump. The authors hypothesized that co-contraction gender differences would be evident with the addition of a perturbed landing in contrast to their previous work[139] which found no gender differences during vertical jump landing. They also hypothesized that adults would exhibit a higher co-contraction ratio during the preparatory landing phase and children would have higher co-contraction during the landing as previously found.[139] EMG surface electrodes (Ag/AgCl pre-gelled) were placed on the biceps femoris, semimembranosus/semitendinosus and vastus medialis. The electrodes were located 2.5cm apart, parallel to the muscle fibers and over the midline between the motor end plate and tendon. The data from the hamstrings muscle sites were averaged. Mean amplitude root mean square (RMS) was calculated at three different time intervals during the trials (100 ms prior to contact, 100 ms after contact and from contact to maximum knee flexion). The EMG signal was normalized to the highest signal during the landing phase of each trial. Co-contraction ratio was calculated by dividing hamstrings by quadriceps EMG activity. A vertical jump was performed at 50% of the subject's maximum jump height during a normal condition (ball placed at subject's midline) and perturbed condition (ball offset 45.7 cm for adults and 30.5 cm for children from midline). The results of the study indicated that during the preparatory phase (100 ms prior to initial contact) the co-contraction ratio was higher in adults compared to children. This was explained by higher hamstring activity relative to quadriceps in adults prior to landing. No gender differences were found with or without the landing perturbation. The authors suggest that increased co-contraction during the preparatory phase is likely a learned feed-forward mechanism as the children did not exhibit similar co-contraction levels.

Discussion

Motor control mechanisms, which may be utilized for joint stability involve feedback (reactive reflex) and feed forward (pre-activated) systems.[57] The electromechanical time delays that are inherent in the feedback mechanism limit the effectiveness of muscular joint protection during dynamic movements, but are better suited for maintaining posture and slower movements.[57] Feed forward mechanisms involves preparatory activation by anticipation of the load or movement.[57] The preparatory activation can be learned and adjusted through integration of previous experiences of the skill or movement. As the individual becomes more experienced, inappropriate muscle co-contraction (decreasing the systems "degrees of freedom") patterns may be replaced by more coordinated muscle firing patterns for the development of appropriate dynamic joint stability and efficient movements. The results from the studies above do not fully support or refute this theory.

Of the six studies reviewed the differences in methodology and results make the synthesis of the author interpretations difficult. For example, three studies addressed co-contraction in landing movements, each with different results. Subjects classified as sedentary[180] did not have different preparatory co-contraction levels compared to active subjects. In another study, low skilled children[147] had higher preparatory co-contraction levels compared to high-skilled children. In contrast, Croce et al.[139] and Russell et al.[183] found that during a landing the preparatory co-contraction levels were higher in the older group compared to younger group. These conflicting results are likely due to differences in tested population and methodologies. Differences in EMG normalization, calculation of co-contraction, electrode placement and signal processing are evident in these studies. A clear delineation of the effects of experience (age or skill level) on muscular co-contraction during a landing from a jump cannot be gleaned based on the differences among the studies. However, it would appear that during landings, co-contraction is generally considered an appropriate motor control strategy used to dynamically stabilize and protect the knee joint. It should also be noted that during landing, the role of hip flexion may complicate the interpretation of co-contraction at the knee based on the differences in uniarticular and biarticular muscles which cross the knee joint.

Sigward and Powers[182], examined a side-step cutting maneuver in a group of female soccer players. They found higher co-contraction during the initial 20% of stance in a novice group compared to skilled group. The joint moment analysis did not appear to support the author interpretation of increased hamstrings contraction in the novice group. A higher internal flexor moment generated during the initial 20% of stance in the skilled group would seem to relate to a net joint moment that is more towards flexor activation in contrast to the presented co-contraction ratio (lower flexor/extensor ratio, co-contraction). The effects of normalization or additional muscle contributions (i.e. gastrocnemius) to the net joint moment may explain the differences. The results of the only study in the review which examined a side-step cut would support the classic motor learning theory which contends that excessive antagonistic contribution during dynamic tasks may decreases the system's "degrees of freedom" during initial acquisition of a new skill.[173-175] However, this may not be the most appropriate "learned" movement pattern in relation to a possible elevated risk of injury.

Walking and running were investigated in two studies. Frost et al.[181] found when running speeds were matched among three age groups (7-8, 10-12, 15-16 years) the younger children had higher co-contraction throughout the trial compared to the mature subjects. During walking, at matched treadmill speeds, the younger age groups also showed a trend toward higher co-contraction when compared to the older age groups. When walking was examined in sedentary and active males and females,[180] the only difference found was a higher co-contraction index in the sedentary females compared to active females. A preparatory co-contraction period (150 ms prior to heel strike) was used in this study. The authors suggested that women with lower work producing capability (as measured on an isokinetic dynamometer at 60°/sec.) have higher preparatory co-contraction. In general, the studies related to walking and running appear to support the hypothesis that during maturation and skill development, inhibition of antagonist muscle groups is thought to be progressively learned until an efficient movement pattern is obtained.[117]

However, multiple discrepancies exist among the studies and make comparisons and conclusions difficult to identify. Differences which may effect co-contraction include: movement, population, methods and interpretation of findings. In the studies that focused on the continuous, phasic nature of gait (walking and running), similar results were observed. For example, the less experienced individuals seemed to exhibit increased co-contraction of the hamstrings and quadriceps. In contrast, the results from different discrete movements (drop jump, vertical jump and side step cut) appear to differ and add complexity to the comparative analyses. Landing and cutting maneuvers are typically examined related to dynamic knee joint stability to protect the joint from excessive load that can cause injury, whereas gait may be more related to questions regarding movement efficiency.

Methodological and Technical Considerations

Muscular co-contraction results vary among studies based on the population and movement task. However, it is clear that technically, the calculation of a co-contraction index or ratio can be extremely complex and vary significantly among studies. Typically, surface EMG is utilized to obtain agonist and antagonist muscular activation patterns. The EMG signal is the electrical representation of neuromuscular activation focused at the neuromuscular endplate related to a contracting muscle.[117] Both extrinsic and intrinsic factors may influence the EMG signal that is detected and recorded.[185] Extrinsic factors may include the electrode configuration, electrode location relative to motor points and lateral edge of muscle and electrode orientation with respect to muscle fibers, among other potential factors.[185] Intrinsic factors, such as the number of active motor units, muscle fiber type, blood flow in the muscle, fiber diameter, depth and location of active muscle fibers, and the amount of tissue between surface of muscle and electrode are other important factors that can affect detectable signal intensity.[185]

In addition to the number of anatomical, physiological and technical factors that may effects recorded EMG signal, the specific processing and analysis of the signal are also important to the reported index or ratio.[186, 187] Kellis[187] reviewed several factors specifically related to quantification of antagonist activation around the knee. The method of normalizing an EMG signal is an important factor that is often carried out differently among studies.[186, 187] Antagonist EMG is typically normalized to reduce variability and/or to relate the signal contribution to the resultant joint moment.[187] Kellis[187] provided discussion in his review how the method of normalization can alter reported results and suggested that standardized methods be considered and a careful interpretation of normalized EMG data was recommended.

Alternative Methods

Alternative methods of examining co-contraction have utilized joint moment analyses, leg and vertical stiffness calculations and model-based estimation of muscle forces. Calculation of joint moments through inverse dynamics incorporates the *net* forces which act about the joint.[116] One limitation of net joint moment analysis is that it does not indicate which muscles are active or the individual muscle forces generated at any specific point in time. Therefore, cautious interpretation of the joint moment to the actual muscle forces is necessary. Joint stiffness calculations involves the resistance of a mechanical stretch by an applied force.[59] Joint stability requires muscle stiffness and may relate to musculoskeletal injury potential.[59] Padua et al.[59] found that females had lower leg stiffness values, in addition to higher quadriceps to hamstrings co-contraction, compared to males. Although, once normalized to mass the stiffness values were not different, females exhibited greater quadriceps activation than males.

Other techniques estimate individual muscle forces through computational models. The agonist and antagonist muscle groups can then be further investigated to address co-contraction during different movements. These computer models represent varying degrees of complexity and require detailed information regarding the muscle and skeletal systems[118]. Erdemir et al. reviewed the various techniques for this type of modeling and provided recommendations for clinical applications[188] These authors suggest that when a clinical problem involves co-contraction and muscle forces cannot be adequately interpreted based on EMG or joint torques, that model-based estimation of individual muscle forces may be necessary.[188] A combination of methods is likely necessary to gain a better understanding of how the neuromuscular system utilizes co-contraction for joint stabilization and coordinated movements in a timely manner.

Conclusions and Further Recommendations

Longitudinal study designs should be employed to address motor control and learning adaptations that may occur throughout development related to co-contraction of hamstrings and quadriceps musculature for both dynamic joint stability and efficient movement patterns. Neuromuscular injury prevention studies may also be beneficial to help address the changes that occur in co-contraction during dynamic activities. The relationship between adequate dynamic joint stability and efficient movement patterns is complex. In high joint force and torque motions, where the hamstrings are activated to increase joint stiffness and stabilize the knee, the effectiveness of the quadriceps may be decreased, requiring greater work and reduction of the efficiency of movement. If individual muscle forces can be estimated during these dynamic movements, then the movement control and loading on the ligaments may be better understood.[188]

Table A.1. Systematic review of co-contraction and age

Study	Subjects	Tasks	Measures	Findings
Frost et al.[181]	Grouped by age (yr) 7-8 (n=10) 10-12 (n=10) 15-16 (n=10)	Treadmill walk Treadmill jog	EMG VO_2	• Co-contraction index higher at running speeds matched to same relative metabolic intensity in younger age subjects • VO_2 higher in younger age at matched speeds
Croce et al.[139]	Grouped by age (yr) Pre-pubescent females (n=15) Pre-pubescent males (n=15) Post-pubescent females (n=14) Pre-pubescent males (n=14)	Vertical jump landing (50% max)	EMG Kinematics	• Co-contraction ratio higher in post-pubescent compared to pre-pubescent prior to landing • Co-contraction ratio lower in post-pubescent compared to pre-pubescent after initial contact
Hamstra-Wright et al.[147]	Pre-pubescent Children Male, high skill (n=11) Male, low skill(n=6) Female, high skill (n=10) Female, low skill (n=9)	Drop jump	EMG Leg stiffness	• Low skilled prepubescent children had greater preparatory co-contraction than high skilled • No differences in vertical leg stiffness between gender or skill level
da Fonseca et al.[180]	Male, athletic (n=9) Male, sedentary (n=9) Female, athletic (n=9) Female, sedentary (n=9)	Walk Jump landing	EMG	• Walking: sedentary females had higher co-contraction levels than athletic females • Landing: no differences between groups
Sigward and Powers[182]	Female, experienced (n=15) Female, novice (n=15)	Side step cut	EMG Inverse dynamics	• Novice athletes had higher co-contraction during early deceleration than experienced athletes • Experience athletes had higher internal knee flexion moments than novice athletes
Russell et al.[183]	Grouped by age (yr) Children - girls (n=14) Children - boys (n=14) Adults - women (n=14) Adults - men (n=13)	Vertical jump landing (50% max, normal and perturbed)	EMG Kinematics	• Adults had higher co-contraction ratio during preparatory landing phase than children • No co-contraction ratio differences between groups during reflexive or voluntary phase • No gender difference in co-contraction ratio

Appendix B. Pubertal Maturation Observation Scale[52]

Table B.1. Female and male PMOS form

Female Characteristic Checklist

_____ The adolescent has grown 3 to 3.5 inches in the past 6 months or is past this growth spurt.
_____ The adolescent has begun breast development.
_____ The adolescent has begun menarche.
_____ The adolescent has evidence of darker underarm hair or shaves.
_____ The adolescent has evidence of darker hair on her legs or shaves.
_____ The adolescent's calves are becoming defined.
_____ The adolescent has evidence of acne.
_____ There was evidence of sweating after physical activities.

Male Characteristic Checklist

_____ The adolescent has evidence of darkening of facial hair or shaves.
_____ The adolescent's voice has gotten deeper or is currently breaking.
_____ The adolescent has grown 3 to 4 inches in the past 6 months or is past the growth spurt.
_____ The adolescent has darker hair on his legs.
_____ The adolescent's biceps are becoming defined.
_____ The adolescent's calves are becoming defined.
_____ The adolescent has evidence of acne.
_____ There was evidence of sweating after physical activities.
_____ There is darkened underarm hair.

KEY:
+ characteristic is present
_ characteristic is absent

SCORING CRITERIA FOR MALES AND FEMALES
STAGES NUMBER OF ‘‘+’’
Prepuberty 1 or less
Pubertal 2 - 5
Postpubertal at least 6; growth spurt completed

Appendix C. Khamis-Roche Method Regression Equations[58]

Table C.1. Female specific regression equations (Khamis-Roche).

Age	B_0	Stature-in	Weight-lbs	Midparent Stature-in
4	-8.1325	1.24768	-0.019435	0.44774
4.5	-6.47656	1.22177	-0.018519	0.41381
5	-5.13582	1.19932	-0.01753	0.38467
5.5	-4.13791	1.1788	-0.016484	0.36039
6	-3.51039	1.15866	-0.0154	0.34105
6.5	-3.14322	1.13737	-0.014294	0.32672
7	-2.87645	1.11342	-0.013184	0.31748
7.5	-2.66291	1.08525	-0.012086	0.3134
8	-2.45559	1.05135	-0.011019	0.31457
8.5	-2.20728	1.01018	-0.009999	0.32105
9	-1.87098	0.9602	-0.009044	0.33291
9.5	-1.0633	0.89989	-0.008171	0.35025
10	0.33468	0.82771	-0.007397	0.37312
10.5	1.97366	0.74213	-0.006739	0.40161
11	3.50436	0.67173	-0.006136	0.42042
11.5	4.57747	0.6415	-0.005518	0.41686
12	4.84365	0.64452	-0.004894	0.3949
12.5	4.27869	0.67386	-0.004272	0.3585
13	3.21417	0.7226	-0.003661	0.31163
13.5	1.83456	0.78383	-0.003067	0.25826
14	0.32425	0.85062	-0.0025	0.20235
14.5	-1.13224	0.91605	-0.001967	0.14787
15	-2.35055	0.97319	-0.001477	0.0988
15.5	-3.10326	1.01514	-0.001037	0.05909
16	-3.17885	1.03496	-0.000655	0.03272
16.5	-2.41657	1.02573	-0.00034	0.02364
17	-0.65579	0.98054	-0.0001	0.03584
17.5	2.26429	0.89246	-0.000057	0.07327

Equations specific for girls.

Table C.2. Male specific regression equations (Khamis-Roche).

Age	B_0	Stature-in	Weight-lbs	Midparent Stature-in
4	-10.2567	1.23812	-0.0087235	0.50286
4.5	-10.719	1.15964	-0.0074454	0.52887
5	-11.0213	1.10674	-0.0064778	0.53919
5.5	-11.1556	1.0748	-0.005776	0.53691
6	-11.1138	1.05923	-0.0052947	0.52513
6.5	-11.0221	1.05542	-0.0049892	0.50692
7	-10.9984	1.05877	-0.0048144	0.48538
7.5	-11.0214	1.06467	-0.0047256	0.46361
8	-11.0696	1.06853	-0.0046778	0.44469
8.5	-11.122	1.06572	-0.0046261	0.43171
9	-11.1571	1.05166	-0.0045254	0.42776
9.5	-11.1405	1.02174	-0.0043311	0.43593
10	-11.038	0.97135	-0.0039981	0.45932
10.5	-10.8286	0.89589	-0.0034814	0.50101
11	-10.4917	0.81239	-0.002905	0.54781
11.5	-10.0065	0.74134	-0.0024167	0.58409
12	-9.3522	0.68325	-0.0020076	0.60927
12.5	-8.6055	0.63869	-0.0016681	0.62279
13	-7.8632	0.60818	-0.0013895	0.62407
13.5	-7.1378	0.59228	-0.0011624	0.61253
14	-6.4299	0.59151	-0.0009776	0.58762
14.5	-5.7578	0.60643	-0.0008261	0.54875
15	-5.1282	0.63757	-0.0006988	0.49536
15.5	-4.5092	0.68548	-0.0005863	0.42687
16	-3.9292	0.75069	-0.0004795	0.34271
16.5	-3.4873	0.83375	-0.0003695	0.24231
17	-3.283	0.9352	-0.000247	0.1251
17.5	-3.4156	1.05558	-0.0001027	-0.0095

Equations specific for boys.

Appendix D. Matlab code

Generate Visual3D pipeline script for each subject

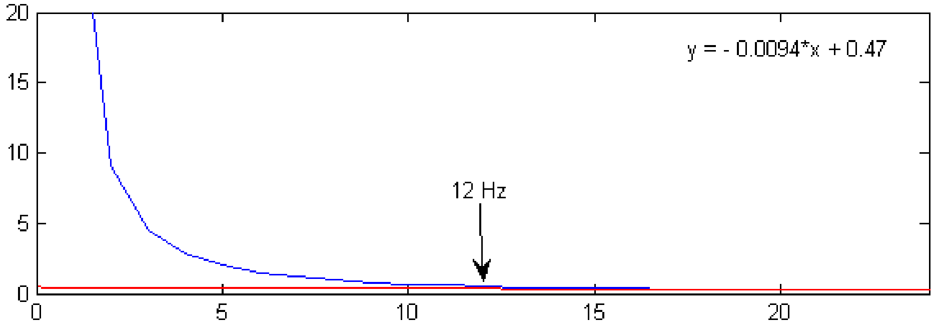
```
[num, txt]= xlsread('G:\Kevin\Visual3D\Code Development\Copy of …
keyfile.xlsx','Sheet3','A2:F1693');  % load keyfile for all subjects

fsize = length(txt);

for a = 1:fsize; %a is the row from the KeyFile

errorcheck = sum(isnan(num(a,1:3))); %sum = 0 if no NaN
            if errorcheck==0;   %continue or end

subjectheight = num2str(num(a,2));
subjectweight = num2str(num(a,3));

subjectcode = ([txt{a,1}]);

% Generate front end script with subject code, height, weight & gender
% need male female switch

datafolder='D:\3DMotion\C3D\';
v3dfile = ['D:\3DMotion\C3D\',subjectcode,'.v3s'];

switch lower(txt{a,5})
   case {'female'}
             mdhfile = 'G:\Kevin\Visual3D\Code Development\newNIHfemale_noUE.mdh';
    otherwise
            mdhfile = 'G:\Kevin\Visual3D\Code Development\newNIHmale_noUE.mdh';
end

staticfile = 'static1.c3d';

% writes a v3d script file for each subject, then calls visual3d program

fid = fopen(v3dfile,'w');

    fprintf(fid,'File_New\r\n');
    fprintf(fid,';\r\n');
    fprintf(fid,'\r\n');

fprintf(fid,'%s\r\n',['Set_Pipeline_Parameter']);
fprintf(fid,'%s\r\n',['/PARAMETER_NAME=DATA_FOLDER']);
fprintf(fid,'%s\r\n',['/PARAMETER_VALUE=',datafolder]);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_SEARCH_FOR=']);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_REPLACE_WITH=']);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_APPEND=']);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Set_Pipeline_Parameter']);
fprintf(fid,'%s\r\n',['/PARAMETER_NAME=SUBJECT']);
```

```
fprintf(fid,'%s\r\n',['/PARAMETER_VALUE=',subjectcode]);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_SEARCH_FOR=']);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_REPLACE_WITH=']);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_APPEND=']);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Set_Pipeline_Parameter']);
fprintf(fid,'%s\r\n',['/PARAMETER_NAME=C3D_STATIC']);
fprintf(fid,'%s\r\n',['/PARAMETER_VALUE=',staticfile]);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_SEARCH_FOR=']);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_REPLACE_WITH=']);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_APPEND=']);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Set_Pipeline_Parameter']);
fprintf(fid,'%s\r\n',['/PARAMETER_NAME=C3D_FILES_BOX']);
fprintf(fid,'%s\r\n',['/PARAMETER_VALUE=box*.c3d']);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_SEARCH_FOR=']);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_REPLACE_WITH=']);
fprintf(fid,'%s\r\n',['! /PARAMETER_VALUE_APPEND=']);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Open_File']);
fprintf(fid,'%s\r\n',['/FILE_NAME=::DATA_FOLDER&::SUBJECT&::C3D_FILES_BOX']);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Create_Hybrid_Model']);
fprintf(fid,'%s\r\n',['/CALIBRATION_FILE=::DATA_FOLDER&::SUBJECT&::C3D_STATIC']);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Apply_Model_Template']);
fprintf(fid,'%s\r\n',['/MODEL_TEMPLATE=',mdhfile]);
fprintf(fid,'%s\r\n',['/CALIBRATION_FILE=::DATA_FOLDER&::SUBJECT&::C3D_STATIC']);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Set_Subject_Weight']);
fprintf(fid,'%s\r\n',['/CALIBRATION_FILE=::DATA_FOLDER&::SUBJECT&::C3D_STATIC']);
fprintf(fid,'%s\r\n',['/WEIGHT=',subjectweight]);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Set_Subject_Height']);
fprintf(fid,'%s\r\n',['/CALIBRATION_FILE=::DATA_FOLDER&::SUBJECT&::C3D_STATIC']);
fprintf(fid,'%s\r\n',['/HEIGHT=',subjectheight]);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Assign_Model_File']);
fprintf(fid,'%s\r\n',['/CALIBRATION_FILE=::DATA_FOLDER&::SUBJECT&::C3D_STATIC']);
fprintf(fid,'%s\r\n',['/MOTION_FILE_NAMES=::DATA_FOLDER&::SUBJECT&::C3D_FILES_BOX']);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Call_Script']);
fprintf(fid,'%s\r\n',['/SCRIPT_FILE_NAME=G:\Kevin\Visual3D\Code Development\new_process_all.v3s']);
fprintf(fid,'%s\r\n',['! /SCRIPT_PATH=']);
fprintf(fid,'%s\r\n',[';']);
fprintf(fid,'%s\r\n',['']);
```

```
fprintf(fid,'%s\r\n',['!File_Save_As']);
fprintf(fid,'%s\r\n',['!/FILE_NAME=::DATA_FOLDER&::SUBJECT&.cmo']);
fprintf(fid,'%s\r\n',['!;']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',['Exit_Workspace']);
fprintf(fid,'%s\r\n',['']);
fprintf(fid,'%s\r\n',[';']);

fclose(fid)

[status,result] = dos(['"C:\Program Files\Visual 3D Beta\Visual3D.exe" /s ',v3dfile]);

end
end
```

Filtering example

```
% Residual Analysis to determine cutoff frequency
% Adapted filter properties from matfiltfilt.m :
% Bogert, A.J. van den, and J.J. de Koning, "On optimal filtering for inverse dynamics analysis," Proc. 9th CSB Congress, Burnaby, B.C., pp. 214-215, 1996.
% Contributed by: Ton van den Bogert (bogert@bme.ri.ccf.org). Please report problems and errors.
% Residual Analysis Ref: Winter 2005, pg50.

clear
trcload=(['mv4_30_dvj_100_1.trc']);

trcdatatmp=dlmread(trcload,'\t',6,0); %Read in the file
trcdatatmp2=trcdatatmp(:,3:end)'; % reorganize to find the zero frames if trimmed
t=[];t = find(sum(trcdatatmp2)~=0);
% startframe=t(1); endframe=t(end);
startframe=t(400); endframe=t(end);
trcdataCUT=trcdatatmp(startframe:endframe,:);

% sampling rate
SFkin=240;
CFkin=12;

for CFkin=1:30; %filter data 1 thru 30 hz

   butterorder = 2;
   [b1,a1] = butter(butterorder,(CFkin/(sqrt(2)-1)^(0.5/butterorder))/(SFkin/2),'low'); %
   filtKIN = filtfilt(b1,a1,trcdataCUT);

   [nr nc] = size(filtKIN);

   for j=1:nr;
      tmp(j,:)=(trcdataCUT(j,:)-filtKIN(j,:)).^2;
   end;

   rms(CFkin,:)=sqrt((sum(tmp(:,:)))/nr);
end
figure(1)
plot(rms(:,3:end-1))

figure(2);
avgres2 = mean(rms(:,3:end-1),2);
plot(avgres2(1:30,1), 'DisplayName', 'avgres(1:30,1)', 'YDataSource', 'avgres(1:30,1)'); figure(gcf)
```



REFERENCES

1. Zelisko JA, Noble HB, Porter M. A comparison of men's and women's professional basketball injuries. *American Journal of Sports Medicine.* 1982;10(5):297-299.

2. Chandy TA, Grana WA. Secondary school athletic injury in boys and girls: A three-year comparison. *Phys Sportsmed.* 1985;13(3):106-111.

3. Malone TR, Hardaker WT, Garrett WE, Feagin JA, Bassett FH. Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *Journal of Southern Orthopaedic Association.* 1993;2(1):36-39.

4. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *Am J Sports Med.* 1995;23(6):694-701.

5. NCAA. *NCAA injury surveillance system summary.* Indianapolis: National Collegiate Athletic Association;2002.

6. Deitch JR, Starkey C, Walters SL, Moseley JB. Injury risk in professional basketball players: a comparison of Women's National Basketball Association and National Basketball Association athletes. *Am J Sports Med.* Jul 2006;34(7):1077-1083.

7. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med.* Nov-Dec 1999;27(6):699-706.

8. de Loes M, Dahlstedt LJ, Thomee R. A 7-year study on risks and costs of knee injuries in male and female youth participants in 12 sports. *Scand J Med Sci Sports.* 2000;10(2):90-97.

9. Freedman KB, Glasgow MT, Glasgow SG, Bernstein J. Anterior Cruciate Ligament Injury and Reconstruction Among University Students. *Clin Orthop Related Res.* 1998;356:208-212.

10. Ruiz AL, Kelly M, Nutton RW. Arthroscopic ACL reconstruction: a 5-9 year follow-up. *Knee.* Sep 2002;9(3):197-200.

11. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24(6):765-773.

12. Besier TF, Lloyd DG, Ackland TR, Cochrane JL. Anticipatory effects on knee joint loading during running and cutting maneuvers. *Med Sci Sports Exerc.* Jul 2001;33(7):1176-1181.

13. Malinzak RA, Colby SM, Kirkendall DT, Yu B, Garrett WE. A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech.* Jun 2001;16(5):438-445.

14. Chappell JD, Yu B, Kirkendall DT, Garrett WE. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med.* Mar-Apr 2002;30(2):261-267.

15. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* Oct 2003;35(10):1745-1750.
16. McLean SG, Huang X, Su A, van den Bogert AJ. Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. *Clin Biomech.* 2004;19:828-838.
17. Ford KR, Myer GD, Toms HE, Hewett TE. Gender differences in the kinematics of unanticipated cutting in young athletes. *Medicine & Science in Sports.* Jan 2005;37(1):124-129.
18. McLean SG, Neal RJ, Myers PT, Walters MR. Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. *Med Sci Sports Exerc.* Jul 1999;31(7):959-968.
19. Hewett T. Neuromuscular and Hormonal Factors Associated With Knee Injuries in Female Athletes: Strategies for Intervention. *Sports Medicine.* 2000;29(5):313-327.
20. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* 2000;8(3):141-150.
21. Hewett TE, Paterno MV, Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop.* 2002;402:76-94.
22. Hewett TE, Riccobene JV, Lindenfeld TN, F.R. N. The effect of neuromuscular training on the incidence of knee injury in female athletes: A prospective study. *Am J Sports Med.* 1999;27(6):699-706.
23. Myklebust G, Engebretsen L, Braekken IH, Skjolberg A, Olsen OE, Bahr R. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin J Sport Med.* Mar 2003;13(2):71-78.
24. Hewett TE, Ford KR, Myer GD. Anterior Cruciate Ligament Injuries in Female Athletes: Part 2, A Meta-analysis of Neuromuscular Interventions Aimed at Injury Prevention. *Am J Sports Med.* Dec 28 2006;34(3):490-498.
25. Bendjaballah MZ, Shirazi-Adl A, Zukor DJ. Finite element analysis of human knee joint in varus-valgus. *Clin Biomech (Bristol, Avon).* Apr 1997;12(3):139-148.
26. Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among female athletes: a systematic review of neuromuscular training interventions. *J Knee Surg.* Jan 2005;18(1):82-88.
27. Hewett TE, Myer GD, Ford KR, et al. Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *Am J Sports Med.* Feb 8 2005;33(4):492-501.
28. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res.* Nov 1995;13(6):930-935.
29. Hewett TE, Myer GD, Ford KR. Anterior Cruciate Ligament Injuries in Female Athletes: Part 1, Mechanisms and Risk Factors. *Am J Sports Med.* Feb 2006;34(2):299-311.

30. Andrish JT. Anterior cruciate ligament injuries in the skeletally immature patient. *Am J Orthop.* 2001;30(2):103-110.

31. Buehler-Yund C. *A longitudinal study of injury rates and risk factors in 5 to 12 year old soccer players*. Cincinnati: Environmental health, University of Cincinnati; 1999.

32. Clanton TO, DeLee JC, Sanders B, Neidre A. Knee ligament injuries in children. *J Bone Joint Surg Am.* 1979;61(8):1195-1201.

33. Gallagher SS, Finison K, Guyer B, Goodenough S. The incidence of injuries among 87,000 Massachusetts children and adolescents: results of the 1980-81 Statewide Childhood Injury Prevention Program Surveillance System. *Am J Public Health.* 1984;74(12):1340-1347.

34. Tursz A, Crost M. Sports-related injuries in children. A study of their characteristics, frequency, and severity, with comparison to other types of accidental injuries. *Am J Sports Med.* 1986;14(4):294-299.

35. Griffin LY, Albohm MJ, Arendt EA, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. *Am J Sports Med.* Sep 2006;34(9):1512-1532.

36. Hewett TE, Myer GD, Ford KR. Decrease in neuromuscular control about the knee with maturation in female athletes. *J Bone Joint Surg Am.* 2004;86-A(8):1601-1608.

37. Ford KR, Myer GD, Hewett TE. Increased Trunk Motion in Female Athletes Compared to Males during Single Leg Landing. *Med Sci Sport Exerc.* 2007;39(5).

38. U.S. Department of Health and Human Services. Physical Activity Guidelines for Americans 2008.

39. Myklebust G, Bahr R. Return to play guidelines after anterior cruciate ligament surgery. *Br J Sports Med.* Mar 2005;39(3):127-131.

40. Lohmander LS, Ostenberg A, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum.* Oct 2004;50(10):3145-3152.

41. Quatman CE, Ford KR, Myer GD, Paterno MV, Hewett TE. The effects of gender and pubertal status on generalized joint laxity in young athletes. *J Sci Med Sport.* Jun 25 2007.

42. Earl JE, Monteiro SK, Snyder KR. Differences in lower extremity kinematics between a bilateral drop-vertical jump and a single-leg step-down. *J Orthop Sports Phys Ther.* May 2007;37(5):245-252.

43. van Mechelen W, Mellenbergh GJ. Problems and Solutions in Longitudinal Research: From Theory to Practice. *Int J Sports Med.* 1997;18(S 3):S238-S245.

44. Beunen G, Malina RM. Growth and physical performance relative to the timing of the adolescent spurt. *Exerc Sport Sci Rev.* 1988;16:503-540.

45. Ford KR, Myer GD, Hewett TE. Reliability of landing 3D motion analysis: implications for longitudinal analyses. *Med Sci Sports Exerc.* Nov 2007;39(11):2021-2028.

46. Holden JP, Selbie WS, Stanhope SJ. A proposed test to support the clinical movement analysis laboratory accreditation process. *Gait Posture.* Jun 2003;17(3):205-213.

47. Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *J Orthop Res.* 1989;7(6):849-860.

48. Piazza SJ, Cavanagh PR. Measurement of the screw-home motion of the knee is sensitive to errors in axis alignment. *J Biomech.* Aug 2000;33(8):1029-1034.

49. Ramakrishnan HK, Kadaba MP. On the estimation of joint kinematics during gait. *J Biomech.* 1991;24(10):969-977.

50. Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Use of an overhead goal alters vertical jump performance and biomechanics. *Journal of Strength and Conditioning Research.* May 2005;19(2):394-399.

51. Quatman CE, Ford KR, Myer GD, Hewett TE. Maturation Leads to Gender Differences in Landing Force and Vertical Jump Performance: A Longitudinal Study. *Am J Sports Med.* May 2006;34(5):806-813.

52. Davies PL, Rose JD. Motor skills of typically developing adolescents: awkwardness or improvement? *Phys Occup Ther Pediatr.* 2000;20(1):19-42.

53. Davies PS. *Assessment of cognitive development in adolescents by means of neuropsychological tasks.* [Dissertation]. Laramie: Dept. of Psychology, University of Wyoming; 1995.

54. Stefanyshyn DJ, Nigg BM. Dynamic angular stiffness of the ankle joint during running and sprinting. / Raideur angulaire dynamique des articulations de la cheville pendant un exercice de course et de sprint. *Journal of Applied Biomechanics.* 1998;14(3):292-299.

55. Malina RM, Bouchard C. *Growth, maturation, and physical activity*. Champaign, Il: Human Kinetics; 1991.

56. Farley CT, Gonzalez O. Leg stiffness and stride frequency in human running. *J Biomech.* Feb 1996;29(2):181-186.

57. Lephart SM, Fu FH. *Proprioception and neuromuscular control in joint stability.* Champaign, IL: Human Kinetics; 2000.

58. Khamis HJ, Roche AF. Predicting adult stature without using skeletal age: the Khamis-Roche method. *Pediatrics.* Oct 1994;94(4 Pt 1):504-507.

59. Padua DA, Carcia CR, Arnold BL, Granata KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *J Mot Behav.* Mar 2005;37(2):111-125.

60. van Mechelen W, Hlobil H, Kemper HC. Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Med.* Aug 1992;14(2):82-99.

61. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med.* Jun 2004;32(4):1002-1012.

62. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23(6):573-578.

63. McNair PJ, Marshall RN, Matheson JA. Important features associated with acute anterior cruciate ligament injury. *N Z Med J.* Nov 14 1990;103(901):537-539.

64. Uhorchak JM, Scoville CR, Williams GN, Arciero RA, St Pierre P, Taylor DC. Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets. *Am J Sports Med.* Nov-Dec 2003;31(6):831-842.

65. Beynnon B, Slauterbeck J, Padua D, Hewett TE. Update on ACL risk factors and prevention strategies in the female athlete. Paper presented at: National Athletic Trainers' Association 52nd Annual Meeting and clinical Symposia2001; LA, California.

66. Myer GD, Ford KR, Hewett T. The Effects of Gender on Quadriceps Muscle Activation Strategies During a Maneuver that Mimics A High ACL Injury Risk Position. *J Electromyogr Kinesiol.* 2005;15(1).

67. Tanner JM, Davies PS. Clinical longitudinal standards for height and height velocity for North American children. *J Pediatr.* 1985;107(3):317-329.

68. Kanamori A, Woo SL, Ma CB, et al. The forces in the anterior cruciate ligament and knee kinematics during a simulated pivot shift test: A human cadaveric study using robotic technology. *Arthroscopy.* Sep 2000;16(6):633-639.

69. Fukuda Y, Woo SL, Loh JC, et al. A quantitative analysis of valgus torque on the ACL: a human cadaveric study. *J Orthop Res.* Nov 2003;21(6):1107-1112.

70. Lloyd DG, Buchanan TS. Strategies of muscular support of varus and valgus isometric loads at the human knee. *J Biomech.* 2001;34(10):1257-1267.

71. Benjaminse A, Habu A, Sell TC, et al. Fatigue alters lower extremity kinematics during a single-leg stop-jump task. *Knee Surg Sports Traumatol Arthrosc.* Apr 2008;16(4):400-407.

72. Chappell JD, Creighton RA, Giuliani C, Yu B, Garrett WE. Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury. *Am J Sports Med.* Feb 2007;35(2):235-241.

73. Chaudhari AM, Lindenfeld TN, Andriacchi TP, et al. Knee and hip loading patterns at different phases in the menstrual cycle: implications for the gender difference in anterior cruciate ligament injury rates. *Am J Sports Med.* May 2007;35(5):793-800.

74. Cortes N, Onate J, Abrantes J, Gagen L, Dowling E, Van Lunen B. Effects of gender and foot-landing techniques on lower extremity kinematics during drop-jump landings. *J Appl Biomech.* Nov 2007;23(4):289-299.

75. Ford KR, Myer GD, Smith RL, Vianello RM, Seiwert SL, Hewett TE. A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. *Clinical Biomechanics.* 2006;21(1):33-40.

76. Garrison JC, Hart JM, Palmieri RM, Kerrigan DC, Ingersoll CD. Comparison of Knee-Joint Moments in Male and Female College Soccer Players During a Single-Leg Landing. *Journal of Sport Rehabilitation.* 2005;14(4):332.

77. Gehring D, Melnyk M, Gollhofer A. Gender and fatigue have influence on knee joint control strategies during landing. *Clin Biomech (Bristol, Avon).* Jan 2009;24(1):82-87.

78. Hart JM, Garrison JC, Palmieri-Smith R, Kerrigan DC, Ingersoll CD. Lower extremity joint moments of collegiate soccer players differ between genders during a forward jump. *J Sport Rehabil.* May 2008;17(2):137-147.

79. Hughes G, Watkins J, Owen N. Gender differences in lower limb frontal plane kinematics during landing. *Sports Biomech.* Sep 2008;7(3):333-341.
80. Jacobs C, Mattacola C. Sex Differences in Eccentric Hip-Abductor Strength and Knee-Joint Kinematics When landing from a Jump. *Journal of Sport Rehabilitation.* 2005;14:346-355.
81. Jacobs CA, Uhl TL, Mattacola CG, Shapiro R, Rayens WS. Hip abductor function and lower extremity landing kinematics: sex differences. *J Athl Train.* Jan-Mar 2007;42(1):76-83.
82. Kernozek TW, Torry MR, H. VH, Cowley H, Tanner S. Gender differences in frontal and sagittal plane biomechanics during drop landings. *Med Sci Sports Exerc.* Jun 2005;37(6):1003-1012; discussion 1013.
83. Kernozek TW, Torry MR, Iwasaki M. Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *Am J Sports Med.* Mar 2008;36(3):554-565.
84. Kiriyama S, Sato H, Takahira N. Gender differences in rotation of the shank during single-legged drop landing and its relation to rotational muscle strength of the knee. *Am J Sports Med.* Jan 2009;37(1):168-174.
85. McLean SG, Fellin RE, Suedekum N, Calabrese G, Passerallo A, Joy S. Impact of fatigue on gender-based high-risk landing strategies. *Med Sci Sports Exerc.* Mar 2007;39(3):502-514.
86. Nagano Y, Ida H, Akai M, Fukubayashi T. Gender differences in knee kinematics and muscle activity during single limb drop landing. *Knee.* Jun 2007;14(3):218-223.
87. Pappas E, Hagins M, Sheikhzadeh A, Nordin M, Rose D. Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. *Clin J Sport Med.* Jul 2007;17(4):263-268.
88. Pappas E, Sheikhzadeh A, Hagins M, Nordin M. The effect of gender and fatigue on the biomechanics of bilateral landings from a jump: Peak values. *Journal of Sports Science & Medicine.* 2007;6(1):77-84.
89. Russell KA, Palmieri RM, Zinder SM, Ingersoll CD. Sex differences in valgus knee angle during a single-leg drop jump. *J Athl Train.* Apr-Jun 2006;41(2):166-171.
90. Swartz EE, Decoster LC, Russell PJ, Croce RV. Effects of Developmental Stage and Sex on Lower Extremity Kinematics and Vertical Ground Reaction Forces During Landing. *J Athl Train.* Mar 2005;40(1):9-14.
91. Wallace BJ, Kernozek TW, Mikat RP, Wright GA, Simons SZ, Wallace KL. A comparison between back squat exercise and vertical jump kinematics: implications for determining anterior cruciate ligament injury risk. *J Strength Cond Res.* Jul 2008;22(4):1249-1258.
92. Yu B, McClure SB, Onate JA, Guskiewicz KM, Kirkendall DT, Garrett WE. Age and gender effects on lower extremity kinematics of youth soccer players in a stop-jump task. *Am J Sports Med.* Sep 2005;33(9):1356-1364.
93. Solomonow M, Baratta R, Zhou BH, et al. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am J Sports Med.* May-Jun 1987;15(3):207-213.

94. Wojtys EM, Huston LJ, Schock HJ, Boylan JP, Ashton-Miller JA. Gender differences in muscular protection of the knee in torsion in size-matched athletes. *J Bone Joint Surg Am.* May 2003;85-A(5):782-789.

95. Dyhre-Poulsen P, Simonsen EB, Voigt M. Dynamic control of muscle stiffness and H reflex modulation during hopping and jumping in man. *J Physiol.* Jun 1991;437:287-304.

96. Wojtys EM, Huston LJ. Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities. *Am J Sports Med.* Jan-Feb 1994;22(1):89-104.

97. Dietz V, Noth J, Schmidtbleicher D. Interaction between pre-activity and stretch reflex in human triceps brachii during landing from forward falls. *J Physiol.* 1981;311:113-125.

98. Beard DJ, Kyberd PJ, Fergusson CM, Dodd CA. Proprioception after rupture of the anterior cruciate ligament. An objective indication of the need for surgery? *J Bone Joint Surg Br.* Mar 1993;75(2):311-315.

99. McCarroll JR, Rettig AC, Shelbourne KD. Anterior cruciate ligament injuries in the young athlete with open physes. *Am J Sports Med.* 1988;16(1):44-47.

100. Tursz A, Crost M. Sports-related injuries in children. A study of their characteristics, frequency, and severity, with comparison to other types of accidental injuries. *Am J Sports Med.* Jul-Aug 1986;14(4):294-299.

101. Shea KG, Pfeiffer R, Wang JH, Curtin M, Apel PJ. Anterior cruciate ligament injury in pediatric and adolescent soccer players: an analysis of insurance data. *J Pediatr Orthop.* Nov-Dec 2004;24(6):623-628.

102. Griffin LY, Agel J, Albohm MJ, et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg.* May-Jun 2000;8(3):141-150.

103. Malina RM, Bouchard C. Timing and sequence of changes in growth, maturation, and performance during adolescence. *Growth, maturation, and physical activity.* Champaign, Il: Human Kinetics; 1991:267-272.

104. Kellis E, Tsitskaris GK, Nikopoulou MD, Moiusikou KC. The evaluation of jumping ability of male and female basketball players according to their chronological age and major leagues. *Journal of Strength and Conditioning Research.* 1999;13(1):40-46.

105. Myer GD, Ford KR, Hewett TE. Methodological approaches and rationale for training to prevent anterior cruciate ligament injuries in female athletes. *Scand J Med Sci Sports.* Oct 2004;14(5):275-285.

106. Solomonow M, Krogsgaard M. Sensorimotor control of knee stability. A review. *Scand J Med Sci Sports.* Apr 2001;11(2):64-80.

107. Lloyd DG, Buchanan TS. A model of load sharing between muscles and soft tissues at the human knee during static tasks. *J Biomech Eng.* Aug 1996;118(3):367-376.

108. McLean SG, Lipfert SW, van den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc.* Jun 2004;36(6):1008-1016.

109. Pollard CD, Davis IM, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. *Clin Biomech.* Dec 2004;19(10):1022-1031.

110. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard Steadman J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech.* Aug 2003;18(7):662-669.

111. Ferber R, McClay Davis I, Williams DS, 3rd, Laughton C. A comparison of within- and between-day reliability of discrete 3D lower extremity variables in runners. *J Orthop Res.* Nov 2002;20(6):1139-1145.

112. Queen RM, Gross MT, Liu HY. Repeatability of lower extremity kinetics and kinematics for standardized and self-selected running speeds. *Gait Posture.* Apr 2006;23(3):282-287.

113. Besier TF, Sturnieks DL, Alderson JA, Lloyd DG. Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *J Biomech.* Aug 2003;36(8):1159-1168.

114. Fleiss JL. *The design and analysis of clinical experiments*. New York: Wiley; 1986.

115. Hopkins WG. Measures of reliability in sports medicine and science. *Sports Med.* Jul 2000;30(1):1-15.

116. Winter DA. *Biomechanics and Motor Control of Human Movement*. 3rd ed. ed. New York: John Wiley & Sons, Inc.; 2005.

117. Basmajian JV. Motor learning and control: a working hypothesis. *Arch Phys Med Rehabil.* Jan 1977;58(1):38-41.

118. Jinha A, Ait-Haddou R, Herzog W. Predictions of co-contraction depend critically on degrees-of-freedom in the musculoskeletal model. *J Biomech.* 2006;39(6):1145-1152.

119. Arampatzis A, Schade F, Walsh M, Bruggemann GP. Influence of leg stiffness and its effect on myodynamic jumping performance. *J Electromyogr Kinesiol.* Oct 2001;11(5):355-364.

120. Granata KP, Padua DA, Wilson SE. Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *J Electromyogr Kinesiol.* Apr 2002;12(2):127-135.

121. Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. *Br J Sports Med.* Jun 2005;39(6):324-329.

122. Zeller BL, McCrory JL, Kibler WB, Uhl TL. Differences in Kinematics and Electromyographic Activity Between Men and Women during the Single-Legged Squat. *Am J Sport Med.* 2003;31(3):449-456.

123. Hewett TE, Ford KR, Myer GD, Wanstrath K, Scheper M. Gender Differences in Hip Adduction Motion and Torque During a Single Leg Agility Maneuver. *J Orthop Res.* 2006;24(3):416-421.

124. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med.* Mar 2007;35(3):359-367.

125. Bell AL, Pedersen DR, Brand RA. A comparison of the accuracy of several hip center location prediction methods. *J Biomech.* 1990;23(6):617-621.

126. de Leva P. Joint center longitudinal positions computed from a selected subset of Chandler's data. *J Biomech.* Sep 1996;29(9):1231-1233.

127. Cole GK, Nigg BM, Ronsky JL, Yeadon MR. Application of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. *J Biomech Eng.* Nov 1993;115(4A):344-349.

128. Andriacchi TP, Natarajan RN, Hurwitz DE. Musculoskeletal Dynamics, Locomotion, and Clinical Applications. In: Mow VC, Hayes WC, eds. *Basic orthopaedic biomechanics*. 2nd ed. Philadelphia: Lippincott-Raven; 1997:37-68.

129. Winter DA. *Biomechanics and Motor Control of Human Movement*. 2nd ed. ed. New York: John Wiley & Sons, Inc.; 1990, pp. 91-95.

130. van den Bogert AJ, de Koning JJ. On optimal filtering for inverse dynamics analysis. Paper presented at: Proceedings of the IXth Biennial Conference of the Canadian Society for Biomechanics1996; Vancouver.

131. Bisseling RW, Hof AL. Handling of impact forces in inverse dynamics. *J Biomech.* 2006;39(13):2438-2444.

132. Schmitz RJ, Shultz SJ, Nguyen AD. Dynamic valgus alignment and functional strength in males and females during maturation. *J Athl Train.* Jan-Feb 2009;44(1):26-32.

133. Tanner JM, Whitehouse RH, Marubini E, Resele LF. The adolescent growth spurt of boys and girls of the Harpenden Growth Study. *Annals of Human Biology.* 1976;3(2):109 - 126.

134. Berns GS, Hull ML, Patterson HA. Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *J Orthop Res.* Mar 1992;10(2):167-176.

135. Beynnon BD, Fleming BC. Anterior cruciate ligament strain in-vivo: a review of previous work. *J Biomech.* Jun 1998;31(6):519-525.

136. Fleming BC, Ohlen G, Renstrom PA, Peura GD, Beynnon BD, Badger GJ. The effects of compressive load and knee joint torque on peak anterior cruciate ligament strains. *Am J Sports Med.* Sep-Oct 2003;31(5):701-707.

137. Shin CS, Chaudhari AM, Andriacchi TP. The effect of isolated valgus moments on ACL strain during single-leg landing: A simulation study. *J Biomech.* Dec 17 2008.

138. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. The effect of an impulsive knee valgus moment on in vitro relative ACL strain during a simulated jump landing. *Clin Biomech (Bristol, Avon).* Nov 2006;21(9):977-983.

139. Croce RV, Russell PJ, Swartz EE, Decoster LC. Knee muscular response strategies differ by developmental level but not gender during jump landing. *Electromyogr Clin Neurophysiol.* Sep 2004;44(6):339-348.

140. Hewett TE, Myer GD, Ford KR, J.L. S. Preparticipation Physical Exam Using a Box Drop Vertical Jump Test in Young Athletes: The Effects of Puberty and Sex. *Clin J Sport Med.* 2006;16(4):298-304.

141. Kellis E, Tsitskaris GK, Nikopoulou MD, Moiusikou KC. The evaluation of jumping ability of male and female basketball players according to their chronological age and major leagues. *J Strength Cond Res.* 1999;13(1):40-46.

142. Myer GD, Ford KR, McLean SG, Hewett TE. The Effects of Plyometric Versus Dynamic Stabilization and Balance Training on Lower Extremity Biomechanics. *Am J Sports Med.* 2006;34(3):490-498.

143. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res.* Feb 2005;19(1):51-60.

144. Granata KP, Wilson SE, Padua D. Gender differences in active musculoskeletal stiffness. Part I. Quantification in controlled measurements of knee joint dynamics. *J Electromyogr Kinesiol.* 2002;12:119-126.

145. Zhang LQ, Wang G. Dynamic and static control of the human knee joint in abduction-adduction. *J Biomech.* Sep 2001;34(9):1107-1115.

146. Hughes G, Watkins J. Lower limb coordination and stiffness during landing from volleyball block jumps. *Res Sports Med.* 2008;16(2):138-154.

147. Hamstra-Wright KL, Swanik CB, Sitler MR, et al. Gender comparisons of dynamic restraint and motor skill in children. *Clin J Sport Med.* Jan 2006;16(1):56-62.

148. Li-i W, Der-Chia L, Chenfu H. Age Effect on Jumping Techniques and Lower Limb Stiffness During Vertical Jump. *Research in Sports Medicine.* 2004;12(3):1-22.

149. Davis RB, DeLuca PA. Gait characterization via dynamic joint stiffness. *Gait & Posture.* 1996;4(3):224-231.

150. Imran A, O'Connor JJ. Theoretical estimates of cruciate ligament forces: effects of tibial surface geometry and ligament orientations. *Proc Inst Mech Eng [H].* 1997;211(6):425-439.

151. Zazulak BT, Ponce PL, Straub SJ, Medvecky MJ, Avedisian L, Hewett TE. Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther.* May 2005;35(5):292-299.

152. Shultz SJ. Preventive training programs: Changing strength ratios versus positions of muscular efficiency. In: Hewett TE, Shultz SJ, Griffin LY, American Orthopaedic Society for Sports Medicine, eds. *Understanding and Preventing Noncontact ACL Injuries*. Champaign, IL: Human Kinetics; 2007:91-101.

153. Wilk KE, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR, Boyd ML. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. *Am J Sports Med.* Jul-Aug 1996;24(4):518-527.

154. Butler RJ, Crowell Iii HP, Davis IMC. Lower extremity stiffness: implications for performance and injury. *Clinical Biomechanics.* 2003;18(6):511-517.

155. Latash ML, Zatsiorsky VM. Joint stiffness: Myth or reality? *Human Movement Science.* 1993;12(6):653-692.

156. Beunen G, Ostyn M, Simons J, et al. Development and tracking in fitness components: Leuven longtudinal study on lifestyle, fitness and health. *Int J Sports Med.* Jul 1997;18 Suppl 3:S171-178.

157. Walsh MS, Bohm H, Butterfield MM, Santhosam J. Gender bias in the effects of arms and countermovement on jumping performance. *J Strength Cond Res.* May 2007;21(2):362-366.

158. Myer GD, Ford KR, Barber Foss KD, Liu C, Nick TG, Hewett TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clin J Sport Med.* Jan 2009;19(1):3-8.

159. Myer GD, Ford KR, Hewett TE. Rationale and Clinical Techniques for Anterior Cruciate Ligament Injury Prevention Among Female Athletes. *J Athl Train.* Dec 2004;39(4):352-364.

160. Sell TC, Ferris CM, Abt JP, et al. Predictors of proximal tibia anterior shear force during a vertical stop-jump. *J Orthop Res.* Dec 2007;25(12):1589-1597.

161. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. *Am J Sports Med.* Feb 2006;34(2):269-274.

162. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. Effect of varying hamstring tension on anterior cruciate ligament strain during in vitro impulsive knee flexion and compression loading. *J Bone Joint Surg Am.* Apr 2008;90(4):815-823.

163. Myer GD, Ford KR, Brent JL, Hewett TE. Differential neuromuscular training effects on ACL injury risk factors in "high-risk" versus "low-risk" athletes. *BMC Musculoskelet Disord.* 2007;8(39):1-7.

164. Steben RE, Steben AH. The validity of the stretch shortening cycle in selected jumping events. *J Sports Med Phys Fitness.* Mar 1981;21(1):28-37.

165. Cavagna GA, Saibene FP, Margaria R. Effect of Negative Work on the Amount of Positive Work Performed by an Isolated Muscle. *J Appl Physiol.* Jan 1965;20:157-158.

166. Newton RU, Kraemer WJ. Developing explosive muscular power: implications for a mixed methods training strategy. *Strength and Conditioning.* 1994;October:20-31.

167. Bobbert MF, Huijing PA, van Ingen Schenau GJ. Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Med Sci Sports Exerc.* Aug 1987;19(4):339-346.

168. Lephart SM, Abt JP, Ferris CM, et al. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med.* Dec 2005;39(12):932-938.

169. Padua DA, Marshall SW, Beutler AI, et al. Predictors of Knee Valgus Angle During a Jump-Landing Task. *Med Sci Sports Exerc.* 2005;37(5):S398.

170. Nagano Y, Sakagami M, Ida H, Akai M, Fukubayashi T. Statistical modelling of knee valgus during a continuous jump test. *Sports Biomech.* Sep 2008;7(3):342-350.

171. McLean SG, Walker K, Ford KR, Myer GD, Hewett TE, van den Bogert AJ. Evaluation of a two dimensional analysis method as a screening tool for anterior cruciate ligament injury. *Br J Sports Med.* Jun 2005;39(6):355-362.

172. Ford KR, van den Bogert AJ, Myer GD, Shapiro R, Hewett TE. The effects of age and skill level on knee musculature co-contraction during functional activities: a systematic review. *Br J Sports Med.* Jul 2008;42(7):561-566.

173. Davids K, Lees A, Burwitz L. Understanding and measuring coordination and control in kicking skills in soccer: implications for talent identification and skill acquisition. *J Sports Sci.* Sep 2000;18(9):703-714.

174. Bernshtein NA. *The co-ordination and regulation of movements*. [1st English ed. Oxford, New York,: Pergamon Press; 1967.

175. Schmidt RA, Lee TD. *Motor control and learning : a behavioral emphasis*. 3rd ed. Champaign, IL: Human Kinetics; 1999.

176. Chmielewski TL, Hurd WJ, Rudolph KS, Axe MJ, Snyder-Mackler L. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. *Phys Ther.* Aug 2005;85(8):740-749; discussion 750-744.

177. MacWilliams BA, Wilson DR, DesJardins JD, Romero J, Chao EY. Hamstrings cocontraction reduces internal rotation, anterior translation, and anterior cruciate ligament load in weight-bearing flexion. *J Orthop Res.* Nov 1999;17(6):817-822.

178. Hewett TE, Myer GD, Zazulak BT. Hamstrings to quadriceps peak torque ratios diverge between sexes with increasing isokinetic angular velocity. *J Sci Med Sport.* Sep 15 2007.

179. Kellis E, Arabatzi F, Papadopoulos C. Muscle co-activation around the knee in drop jumping using the co-contraction index. *J Electromyogr Kinesiol.* Jun 2003;13(3):229-238.

180. da Fonseca ST, Vaz DV, de Aquino CF, Bricio RS. Muscular co-contraction during walking and landing from a jump: comparison between genders and influence of activity level. *J Electromyogr Kinesiol.* Jun 2006;16(3):273-280.

181. Frost G, Bar-Or O, Dowling J, Dyson K. Explaining differences in the metabolic cost and efficiency of treadmill locomotion in children. *J Sports Sci.* Jun 2002;20(6):451-461.

182. Sigward S, Powers CM. The influence of experience on knee mechanics during side-step cutting in females. *Clin Biomech (Bristol, Avon).* Aug 2006;21(7):740-747.

183. Russell PJ, Croce RV, Swartz EE, Decoster LC. Knee-muscle activation during landings: developmental and gender comparisons. *Med Sci Sports Exerc.* Jan 2007;39(1):159-170.

184. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc.* Jan 2003;35(1):119-127.

185. Cacciari E, Milani S, Balsamo A, et al. Italian cross-sectional growth charts for height, weight and BMI (6-20 y). *Eur J Clin Nutr.* 2002;56(2):171-180.

186. Shultz SJ, Perrin DH. Using Surface Electromyography To Assess Sex Differences in Neuromuscular Response Characteristics. *J Athl Train.* Apr 1999;34(2):165-176.

187. Kellis E. Quantification of quadriceps and hamstring antagonist activity. *Sports Med.* Jan 1998;25(1):37-62.

188. Erdemir A, McLean S, Herzog W, van den Bogert AJ. Model-based estimation of muscle forces exerted during movements. *Clin Biomech.* Oct 26 2006.

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Scholastic and Professional Honors:

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American College of Sports Medicine - Biomechanics Interest Group Student Research Award (2008), Effect of drop height on lower extremity biomechanical measures in female athletes.

O'Donoghue Award (2005), The American Orthopaedic Society for Sports Medicine. Biomechanical measures of neuromuscular control and valgus loading of the knee predict ACL injury risk in female athletes: a prospective study.

First Runner-up (2004) Journal of Athletic Training, Clint Thompson Award for Outstanding Non-Research Manuscript.

Professional Publications - Manuscripts:

Ford KR, Myer GD, Brent JL, Hewett TE. Hip and knee extensor moments predict vertical jump height in adolescent girls. *J Strength Cond Res.* 2009;In Press.

Myer GD, Ford KR, Divine JG, Wall EJ, Kahanov L, Hewett TE. Longitudinal Assessment of Noncontact Anterior Cruciate Ligament Injury Risk Factors During Maturation in a Female Athlete: A Case Report. *J Athl Train.* 2009;44(1).

Barber-Foss K, Ford KR, Myer GD, Hewett TE. Increased Generalized Joint Laxity Associated with Increased Medial Foot Loading in Female Athletes. *J Athl Train.* 2009;In Press.

Hewett TE, Lynch TR, Ford KR, Gwin RC, Heidt RS, Jr., Myer GD. Multiple Risk Factors Related to Familial Predisposition to Anterior Cruciate Ligament Injury: Fraternal Twin Sisters with Ipsilateral ACL ruptures. *Br J Sports Med.* 2009;In Press.

Hickey KC, Quatman CE, Myer GD, Ford KR, Brosky T, Hewett TE. Dynamic Field Tests used in an NFL Combine Setting to Identify Lower Extremity Functional Asymmetries. *J Strength Cond Res.* 2009;In Press.

Imwalle LE, Myer GD, Ford KR, Hewett TE. The relationship between hip and knee kinematics in female athletes during cutting maneuvers: A possible link to non-contact ACL injury and prevention. *J Strength Cond Res.* 2009;In Press.

Myer GD, Ford KR, Barber Foss KD, Liu C, Nick TG, Hewett TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clin J Sport Med.* Jan 2009;19(1):3-8.

Ford KR, van den Bogert AJ, Myer GD, Shapiro R, Hewett TE. The effects of age and skill level on knee musculature co-contraction during functional activities: a systematic review. *Br J Sports Med.* Jul 2008;42(7):561-566.

Burkhart BG, Ford KR, Myer GD, Heidt RS, Jr., Hewett TE. Anterior Cruciate Ligament Tear in an Athlete: Does Increased Heel Loading Increase ACL Injury Risk? *North American Journal of Sports Physical Therapy.* 2008;3(3).

Mitchell LC, Ford KR, Minning SJ, Myer GD, Manigne RE, Hewett TE. Effect of medial foot loading pattern on ankle and knee landing biomechanics. *North American Journal of Sports Physical Therapy.* 2008;3(3).

Myer GD, Paterno MV, Ford KR, Hewett TE. Neuromuscular Training Techniques to Target Deficits Before Return to Sport After Anterior Cruciate Ligament Reconstruction. *J Strength Cond Res.* Apr 15 2008;22(3):987-1014.

Quatman CE, Ford KR, Myer GD, Paterno MV, Hewett TE. The effects of gender and pubertal status on generalized joint laxity in young athletes. *J Sci Med Sport.* Jun 25 2008;11(3):257-263.

Archdeacon M, Ford KR, Wyrick J, Paterno MV, Hampton S, Ludwig MB, Hewett TE. A prospective functional outcome and motion analysis evaluation of the hip abductors after femur fracture and antegrade nailing. *J Orthop Trauma.* Jan 2008;22(1):3-9.

Myer GD, Brent JL, Ford KR, Hewett TE. A pilot study to determine the effect of trunk and hip focused neuromuscular training on hip and knee isokinetic strength. *Br J Sports Med.* Mar 4 2008.

Myer GD, Ford KR, Paterno MV, Nick TG, Hewett TE. The Effects of Generalized Joint Laxity on Risk of Anterior Cruciate Ligament Injury in Young Female Athletes. *Am J Sports Med.* Mar 12 2008.

Myer GD, Ford KR, Brent JL, Hewett TE. Differential neuromuscular training effects on ACL injury risk factors in "high-risk" versus "low-risk" athletes. *BMC Musculoskelet Disord.* 2007;8(39):1-7.

Ford KR, Myer GD, Hewett TE. Reliability of landing 3D motion analysis: implications for longitudinal analyses. *Med Sci Sports Exerc.* Nov 2007;39(11):2021-2028.

Hewett TE, Ford KR, Levine P, Page SJ. Reaching kinematics to measure motor changes after mental practice in stroke. *Top Stroke Rehabil.* Jul-Aug 2007;14(4):23-29.

Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin J Sport Med.* Jul 2007;17(4):258-262.

Smith R, Ford KR, Myer GD, Holleran A, Treadway E, Hewett TE. Biomechanical and performance differences between female soccer athletes in National Collegiate Athletic Association Divisions I and III. *J Athl Train.* Oct-Dec 2007;42(4):470-476.

Myer GD, Ford KR, Brent JL, Divine JG, Hewett TE. Predictors of Sprint Start Speed: The Effects of Resistive Ground Based vs Inclined Treadmill Training *J Strength Cond Res.* 2007;21(2):491-496.

Ford KR, Manson NA, Evans BJ, Myer GD, Gwin RC, Heidt RS, Jr., Hewett TE. Comparison of in-shoe foot loading patterns on natural grass and synthetic turf. *J Sci Med Sport.* Dec 2006;9(6):433-440.

Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after Anterior Cruciate Ligament Reconstruction: Criteria Based Progression Through the Return to Sport Phase. *J Orthop Sports Phys Ther.* 2006;36(6):385-402.

Quatman CE, Ford KR, Myer GD, Hewett TE. Maturation Leads to Gender Differences in Landing Force and Vertical Jump Performance: A Longitudinal Study. *Am J Sports Med.* May 2006;34(5):806-813.

Hewett TE, Myer GD, Ford KR, J.L. S. Preparticipation Physical Exam Using a Box Drop Vertical Jump Test in Young Athletes: The Effects of Puberty and Sex. *Clin J Sport Med.* 2006;16(4):298-304.

Paterno MV, Archdeacon MT, Ford KR, Galvin D, Hewett TE. Early rehabilitation following surgical fixation of a femoral shaft fracture. *Phys Ther.* Apr 2006;86(4):558-572.

Walsh MS, Ford KR, Bangen KJ, Myer GD, Hewett TE. The validation of a portable force plate for measuring force-time data during jumping and landing tasks. *J Strength Cond Res.* Nov 2006;20(4):730-734.

Hewett TE, Ford KR, Myer GD. Anterior Cruciate Ligament Injuries in Female Athletes: Part 2, A Meta-analysis of Neuromuscular Interventions Aimed at Injury Prevention. *Am J Sports Med.* Dec 28 2006;34(3):490-498.

Hewett TE, Ford KR, Myer GD, Wanstrath K, Scheper M. Gender Differences in Hip Adduction Motion and Torque During a Single Leg Agility Maneuver. *J Orthop Res.* 2006;24(3):416-421.

Myer GD, Ford KR, McLean SG, Hewett TE. The Effects of Plyometric Versus Dynamic Stabilization and Balance Training on Lower Extremity Biomechanics. *Am J Sports Med.* 2006;34(3):490-498.

Hewett TE, Myer GD, Ford KR. Anterior Cruciate Ligament Injuries in Female Athletes: Part 1, Mechanisms and Risk Factors. *Am J Sports Med.* Feb 2006;34(2):299-311.

Myer GD, Ford KR, Brent JL, Hewett TE. The Effects of Plyometric versus Dynamic Balance Training on Power, Balance and Landing Force in Female Athletes. *J Strength Cond Res.* 2006;20(2):345-353.

Cowley HR, Ford KR, Myer GD, Kernozek TW, Hewett TE. Differences in neuromuscular strategies between landing and cutting tasks in female basketball and soccer athletes. *Journal of Athletic Training.* 2006;41(1):67-73.

Ford KR, Myer GD, Smith RL, Vianello RM, Seiwert SL, Hewett TE. A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. *Clinical Biomechanics.* 2006;21(1):33-40.

Myer GD, Ford KR, hewett tE. Preventing ACL injuries in Women. *J Musculoskel Med.* 2006;23(1):12-38.

Myer GD, Brunner HI, Melson PG, Paterno MV, Ford KR, Hewett TE. Specialized neuromuscular training to improve neuromuscular function and biomechanics in a patient with quiescent juvenile rheumatoid arthritis. *Phys Ther.* Aug 2005;85(8):791-802.

Hewett TE, Zazulak BT, Myer GD, Ford KR. A review of electromyographic activation levels, timing differences, and increased anterior cruciate ligament injury incidence in female athletes. *Br J Sports Med.* 2005;39(6):347-350.

McLean SG, Walker K, Ford KR, Myer GD, Hewett TE, van den Bogert AJ. Evaluation of a two dimensional analysis method as a screening tool for anterior cruciate ligament injury. *Br J Sports Med.* Jun 2005;39(6):355-362.

Hewett TE, Myer GD, Ford KR, Heidt RS, Jr., Colosimo AJ, McLean SG, van den Bogert AJ, Paterno MV, Succop P. Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *Am J Sports Med.* Feb 8 2005;33(4):492-501.

Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Use of an overhead goal alters vertical jump performance and biomechanics. *Journal of Strength and Conditioning Research.* May 2005;19(2):394-399.

Myer GD, Ford KR, Hewett TE. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *J Electromyogr Kinesiol.* Apr 2005;15(2):181-189.

Ford KR, Myer GD, Toms HE, Hewett TE. Gender differences in the kinematics of unanticipated cutting in young athletes. *Medicine & Science in Sports.* Jan 2005;37(1):124-129.

Hewett TE, Myer GD, Ford KR. Reducing knee and anterior cruciate ligament injuries among female athletes: a systematic review of neuromuscular training interventions. *J Knee Surg.* Jan 2005;18(1):82-88.

Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res.* Feb 2005;19(1):51-60.

Hewett TE, Myer GD, Ford KR. Decrease in neuromuscular control about the knee with maturation in female athletes. *J Bone Joint Surg Am.* 2004;86-A(8):1601-1608.

Paterno MV, Myer GD, Ford KR, Hewett TE. Neuromuscular training improves single-limb stability in young female athletes. *J Orthop Sports Phys Ther.* 2004;34(6):305-317.

Myer GD, Ford KR, Hewett TE. Methodological approaches and rationale for training to prevent anterior cruciate ligament injuries in female athletes. *Scand J Med Sci Sports.* Oct 2004;14(5):275-285.

Myer GD, Ford KR, Hewett TE. Rationale and Clinical Techniques for Anterior Cruciate Ligament Injury Prevention Among Female Athletes. *J Athl Train.* Dec 2004;39(4):352-364.

Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* Oct 2003;35(10):1745-1750.

Brindle TJ, Nyland J, Ford K, Coppola A, Shapiro R. Electromyographic comparison of standard and modified closed-chain isometric knee extension exercises. *J Strength Cond Res.* Feb 2002;16(1):129-134.

Hewett TE, Myer GD, Ford KR. Prevention of anterior cruciate ligament injuries. *Current Women's Health Reports.* 2001 2001;1(3):218-224.

Professional Publications – Book Chapters:

Myer GD, Paterno MV, Ford, KR and Hewett TE. DeLee and Drez's Orthopaedic Sports Medicine, 3rd ed. Return to Sport Plyometric Training in the Rehabilitation of Athletes Following Anterior Cruciate Ligament Reconstruction 2009. In Press

Hewett TE, Myer GD, Ford KR. Theories on How Interventions May Influence ACL Injury Rates: Changing Landing Techniques and Improving Balance in Intervention Studies. In: Hewett TE, Shultz SJ, Griffin LY, American Orthopaedic Society for Sports Medicine, eds. *Understanding and Preventing Noncontact ACL Injuries*. Champaign, IL: Human Kinetics; 2007:75-90.

Hewett TE, Myer GD, Ford KR, Slauterbeck JR. Dynamic neuromuscular analysis training for preventing anterior cruciate ligament injury in female athletes. *Instr Course Lect.* 2007;56:397-406.

Myer GD, Paterno MV, Ford KR, and Hewett TE. SPTS Home Study Course The Sequence of Prevention: A Systematic Approach to Prevent Anterior Cruciate Ligament Injury in Female Athletes, 2007.

Professional Publications – Published Abstracts:

Minning SJ, Ford KR, Myer GD, Mangine RE, Colosimo AJ, Hewett TE. Landing Adaptations Following Isolated Lateral Meniscus Tears in Athletes. Paper presented at: American Orthopaedic Society of Sports Medicine Specialty Day, 2009; Las Vegas, NV.

Quatman CE, Kiapour A, Ford KR, Myer GD, Kenter K, Demetropoulos C, Hewett TE, Goel VK. ACL and MCL Stresses and Strains during Landings from Jumps: Finite Element Investigation. Paper presented at: AAOS National Meeting, 2009; Las Vegas, NV.

Brent JL, Myer GD, Ford KR, Hewett TE. A Longitudinal Examination of Hip Abduction Strength in Adolescent Males and Females. *Med Sci Sport Exerc.* 2008;40(5).

Burkhart BG, Ford KR, Myer GD, Heidt RS, Hewett TE. Anterior Cruciate Ligament Tear in an Athlete: Does Increased Heel Loading Increase ACL Injury Risk? A Case Report. *Med Sci Sport Exerc.* 2008;40(5).

Divine JD, Myer GD, Ford KR, Wall EJ, Kahanov L, Hewett TE. Longitudinal assessment of non-contact anterior cruciate ligament injury risk factors during maturation. *Med Sci Sport Exerc.* 2008;40(5).

Ford KR, Myer GD, Schmitt LC, van den Bogert AJ, Hewett TE. Effect of drop height on lower extremity biomechanical measures in female athletes. *Med Sci Sport Exerc.* 2008;40(5).

Harrison AD, Myer GD, Ford KR, Hewett TE. Predictors of Vertical Ground Reaction Forces during Maximal Single-leg Vertical Hopping in Young Athletes. *Med Sci Sport Exerc.* 2008;40(5).

Myer GD, Brent JL, Ford KR, Hewett TE. The effect of trunk and hip focused neuromuscular training on hip and knee isokinetic strength. *Med Sci Sport Exerc.* 2008;40(5).

Brent JL, Myer GD, Ford KR, Hewett TE. A Longitudinal Examination of Hip Abduction Strength in Adolescent Males and Females. Paper presented at:

National Strength and Conditioning Association National Meeting, 2008; Las Vegas, NV.

Ford KR, van den Bogert AJ, Myer GD, Shapiro S, Hewett TE. Validation of agonist and antagonist muscle force estimation during jumping at three different effort levels. Paper presented at: North American Congress on Biomechanics, 2008; Ann Arbor Michigan.

Harrison AD, Ford KR, Myer GD, Hewett TE. Effect of Gender on Force Attenuation Strategies During Single Leg Maximal Effort Hopping Utilizing a Portable Forceplate. Paper presented at: Combined Sections Meeting, American Physical Therapy Association, 2008; Nashville, TN.

Kiefer AW, Ford KR, Paterno MV, Myer GD, Riley MA, Shockley K, Hewett TE. Decreased Stability of Multisegmental Postural coordination in ACL-Injured Female Athletes. Paper presented at: North American Congress on Biomechanics, 2008; Ann Arbor, MI.

Myer GD, Ford KR, Foss K, Liu C, Nick TG, Hewett TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. Paper presented at: National Strength and Conditioning Association National Meeting, 2008; Las Vegas, NV.

Paterno MV, Ford KR, Myer GD, Hewett TE. Side-to-side comparisons of postural stability following anterior cruciate ligament reconstruction. Paper presented at: Combined Sections Meeting, American Physical Therapy Association, 2008; Nashville Tennessee.

Schmitt LC, Ford KR, Myer GD, Hewett TE. Lateral Landing Strategies: Analysis of Increased Potential Risk for ACL Injury? Paper presented at: Combined Sections Meeting, American Physical Therapy Association, 2008; Nashville Tennessee.

Brent JL, Ford KR, Myer GD, Hewett TE. Criterion Validity of a Test Utilized to Identify Bilateral Asymmetries in ACL Reconstructed Athletes. *Med Sci Sport Exerc.* 2007;39(5).

Divine JD, Heyl R, Ford KR, Myer GD, Foss K. Gender-Specific Concussion Outcomes in Young Athletes. *Med Sci Sport Exerc.* 2007;39(5).

Ford KR, Myer GD, Hewett TE. Increased Trunk Motion in Female Athletes Compared to Males during Single Leg Landing. *Med Sci Sport Exerc.* 2007;39(5).

Hickey KC, Myer GD, Ford KR, Hewett TE. Within and Between Session Reliability of Dynamic Tests Designed to Isolate Bilateral Asymmetries in Athletes. *Med Sci Sport Exerc.* 2007;39(5).

Lynch TR, Myer GD, Ford KR, Gwin RC, Heidt RS, Shelbourne KD, Hewett TE. Knee Abduction Angle and Notch Width are Potential Factors Related to Familial

Predisposition to Anterior Cruciate Ligament Injury: A Case Report of Fraternal Twins. *Med Sci Sport Exerc.* 2007;39(5).

Myer GD, Ford KR, Hewett TE. Neuromuscular Training Effects on Knee Injury Risk Factors: “High” vs. “Low” Risk Categorized Female Athletes. *Med Sci Sport Exerc.* 2007;39(5).

Manson NA, Ford KR, Myer GD, Evans B, Gwin RC, Heidt RS, Hewett TE. Comparison of In-Shoe Foot Loading Patterns in Football Players on Synthetic Turf. Paper presented at: The American Orthopaedic Association Annual Meeting, 2007; Asheville, North Carolina.

Paterno MV, Ford KR, Myer GD, Hewett TE. A Prospective Longitudinal Analysis of Sex Differences in Knee Laxity During Growth and Development in Adolescents. Paper presented at: Combined Sections Meeting, American Physical Therapy Association, 2007; Boston, Massachusetts.

Brent JL, Myer GD, Ford KR, Hewett TE. The Effect of Gender and Age on Isokinetic Hip Abduction Torques. *Med Sci Sport Exerc.* 2006;38(5).

Ford KR, Manson NA, Evans B, Myer GD, Gwin RC, Heidt RS, Hewett TE. Comparison of In-Shoe Foot Loading Patterns in Football Players on Natural Grass and Synthetic Turf. *Med Sci Sport Exerc.* 2006;38(5).

Manson NA, Ford KR, Evans B, Myer GD, Gwin RC, Heidt RS, Hewett TE. Comparison of In-Shoe Foot Loading Patterns in Football Players on Synthetic Turf. *Med Sci Sport Exerc.* 2006;38(5).

Myer GD, Imwalle L, Ford KR, Hewett TE. Hip Adduction, Not Hip Internal Rotation, Dictates Knee Motion Related to ACL Injury During Cutting Maneuvers. *Med Sci Sport Exerc.* 2006;38(5).

Doten KM, Myer GD, Ford KR, Paterno MV, Hewett TE. The reliability of measures taken during maximal effort vertical hopping. Paper presented at: Combined Sections Meeting, American Physical Therapy Association, 2006; San Diego, California.

Hewett TE, Myer GD, Ford KR. Biomechanical-Epidemiological Studies Show Valgus Measures Predict ACL Injury Risk. Paper presented at: ACL Study Group Retreat, 2006; Kohala Coast, Hawaii.

Hewett TE, Myer GD, Ford KR. Passive and Dynamic Restraints Determine Risk of ACL Injury in Female Athletes. Paper presented at: Orthopaedic Research Society Annual Meeting, 2006; Chicago, Illinois.

Paterno MV, Ford KR, Myer GD, Hewett TE. Vertical hopping and isokinetic strength assessment to determine ACL rehabilitation status. Paper presented at: Combined

Sections Meeting, American Physical Therapy Association, 2006; San Diego, California.

Brent JL, Ford KR, Myer GD, Harrison AD, Hewett TE. Reliability of single leg landings on a portable force platform. *Med Sci Sport Exerc.* 2005;37(5).

Divine JD, Myer GD, Ford KR, Hewett TE. Effects of Resistive Ground Based Training and High Velocity Treadmill Assisted Training and on Sprint Speed. *Med Sci Sport Exerc.* 2005;37(5).

Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Effects of an overhead goal on drop vertical jump maneuvers. *Med Sci Sport Exerc.* 2005;37(5).

Hewett TE, Ford KR, Myer GD, Slauterbeck JR. Effect of puberty and gender on landing force and jump height. *Med Sci Sport Exerc.* 2005;37(5).

Myer GD, Ford KR, Brent JL, Hewett TE. Effects of Plyometric vs Dynamic Balance Neuromuscular Training on Strength and Force Dissipation. *Med Sci Sport Exerc.* 2005;35(5).

Vallabhajosula S, Ford KR, Paterno MV, Myer GD, Divine JD, Hewett TE. Effect of changes in ball weight on shoulder rotations during upper body plyometrics. *Med Sci Sport Exerc.* 2005;37(5).

Hewett TE, Ford KR, Page SJ. Mental practice causes functional and kinematic changes in chronic stroke. *Stroke.* 2005;36(2):422.

Cowley HR, Ford KR, Myer GD, Kernozek TW, Hewett TE. Differences in Neuromuscular Control Strategies with Landing and Cutting Biomechancis in Female Basketball and Soccer Players. Paper presented at: Orthopaedic Research Society, 2005; Washington D.C.

Cowley HR, Ford KR, Myer GD, Kernozek TW, Hewett TE. Bilateral Asymmetry in Joint moments During Cutting and Landing Maneuvers in Four Different Populations of High School Female Athletes. Paper presented at: American Physical Therapy Association Combined Sections Meeting, 2005; New Orleans, Lousiana.

Ford KR, Myer GD, Hewett TE. Effects of Gender on Knee Abduction and Flexion During Medial and Lateral Drop Landings. Paper presented at: International Society for Biomechanics Annual Meeting, 2005; Cleveland, Ohio.

Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Effects of an overhead goal on drop vertical jump maneuvers. Paper presented at: American Physical Therapy Association National Meeting, 2005; Boston, Massachusetts.

Hewett TE, Ford KR, Myer GD, Slauterbeck JR. Large Scale Screening of Vertical Jump Height and Landing Force in Young Athletes. Paper presented at: American Orthopaedic Society for Sports Medicine Annual Meeting, 2005; Keystone, CO.

Hewett TE, Ford KR, Myer GD, Wanstrath K, Scheper M. Sex Differences in Hip Adduction Motion and Torque in Collegiate Athletes. Paper presented at: 1st Annual Oslo Sports Injury Conference, 2005; Oslo, Norway.

Hewett TE, Ford KR, Myer GD, Wanstrath K, Scheper M. Gender Differences in Hip Adduction and Torque in Collegiate Athletes. Paper presented at: Orthopaedic Research Society, 2005; Washington D.C.

Hewett TE, Myer GD, Ford KR. Coupled Biomechanical-Epidemiological Studies for the Assessment of ACL Injury Risk. Paper presented at: International Society for Biomechanics Annual Meeting, 2005; Cleveland, Ohio.

Imwalle L, Myer GD, Ford KR, Hewett TE. Hip Adduction, not Internal Rotation, Dictates Knee Motion Related to ACL Injury Duirng Cutting Maneuvers. Paper presented at: Medical Student Summer Research Program, 2005; Cincinnati, Ohio.

Melson PG, Brunner HI, Ford KR, Myer GD, Darnell SC, Ranz JV, Hewett TE. The Use of Three Dimensional Motion Analysis (MA) to Improve Objective Measurement of Lower Extremity Joint Function and Detect Clinical Changes in Children with Juvenile Idiopathic Arthritis (JIA). Paper presented at: American College of Rheumatology 2005; San Diego, California.

Myer GD, Ford KR, Brent JL, Hewett TE. The Effects of Plyometric versus Dynamic Balance Training on Landing Force and Center of Pressure Stabilization in Female Athletes. Paper presented at: 1st Annual Oslo Sports Injury Conference, 2005; Oslo, Norway.

Myer GD, Ford KR, Brent JL, Hewett TE. Plyometric vs Balance Training: Effects on Power and Force Dissipation. Paper presented at: American Orthopaedic Society for Sports Medicine Annual Meeting, 2005; Keystone, CO.

Myer GD, Ford KR, McLean SG, Hewett TE. The Effects of Plyometric versus Dynamic Balance Training on Lower Extremity Biomechanics in Female Athletes. Paper presented at: International Society for Biomechanics Annual Meeting, 2005; Cleveland, Ohio.

Quatman CE, Ford KR, Myer GD, Hewett TE. Neuromuscular Spurt: Effects of Maturation and Gender. Paper presented at: The American Orthopaedic Society for Sports Medicine Specialty Day, 2005; Washington D.C.

Toetz C, Divine JD, Ford KR, Myer GD, Hewett TE. Patients with Patellofemoral Pain Syndrome Demonstrate Increased Knee Abduction During Landing. Paper presented at: Medical Student Summer Research Program, 2005; Cincinnati, Ohio.

Walsh M, Ford KR, Bangen K, Myer GD, Hewett TE. The Validation of a Portable Force Plate for Measuring Force-Time Data During Jumping and Landing Tasks. Paper presented at: The International Society of Biomechanics and Sports, 2005; Beijing, China.

Ford KR, Myer GD, Divine JD, Hewett TE. Landing differences in high school female soccer players grouped by age. *Med Sci Sport Exerc.* 2004;36(5).

Hewett TE, Myer GD, Ford KR, Heidt RS, Colosimo AJ, McLean SG, Bogert AJ, Paterno MV, Succop P. Neuromuscular control and valgus loading of the knee predict ACL injury risk in female athletes. *Med Sci Sport Exerc.* 2004;36(5).

Myer GD, Ford KR, Paterno MV, Divine JD, Hewett TE. Specialized dynamic neuromuscular training can be used to induce neuromuscular spurt in female athletes. *Med Sci Sport Exerc.* 2004;36(5).

Paterno MV, Myer GD, Ford KR, Hewett TE. Neuromuscular training improves postural stability in young female athletes. *Med Sci Sport Exerc.* 2004;36(5).

Brunner HI, Melson PG, Ford KR, Darnell SC, Myer GD, Ranz JV, Hewett TE. Improved Assessment of Physical Function in Children with Juvenile Idiopathic Arthritis (JIA) Using Biomechanical Testing (BMeT). Paper presented at: American College of Rheumatology, 2004; San Antonio, Texas.

Hewett TE, Myer GD, Ford KR. Neuromuscular training improves performance and lower extremity biomechanics in female athletes. Paper presented at: The Annual American Academy of Orthopaedic Surgeons Meeting, 2004; San Francisco, California.

Thomson K, Ford KR, Myer GD, Smith RL, Heidt RS, Hewett TE. Navicular Drop and Ankle Eversion in Anterior Cruciate Ligament Reconstructed Knees. Paper presented at: Annual Gait and Clinical Movement Society Meeting, 2004; Lexington, Kentucky.

Brunner HI, Paterno MV, Melson PG, Ford KR, Myer GD, Lovell DJ, Hewett TE. Pilot study: improvement of joint use in quiescent juvenile idiopathic arthritis (JIA) with specialized neuromuscular training (SNT) after biomechanical testing. Paper presented at: American Academy of Pediatrics Pediatric Rheumatology, 2003; Snowmass, CO.

Ford KR, Myer GD, Hewett TE. Reliability of dynamic knee motion in female athletes. Paper presented at: American Society of Biomechanics Annual Meeting, 2003; Toledo, OH.

Hewett TE, Ford KR, Myer GD, Toms HE. Effects of gender on knee kinematics during an unanticipated pivoting maneuver. Paper presented at: Orthopaedic Research Society, 2003.

Hewett TE, Myer GD, Ford KR, Slauterbeck JR. A 2-d method for analysis of valgus knee motion in pubertal high-risk athletes. Paper presented at: Annual Meeting of the Orthopaedic Research Society, 2003; New Orleans, LA.

Hewett TE, Myer GD, Ford KR, Toms HE. Puberty decreases 3-D dynamic knee stability in female athletes: a mechanism for increased ACL injury? Paper presented at: Orthopaedic Research Society, 2003.

Ford KR, Myer GD, Hewett TE. Method for 2-dimensional analysis of abnormal medial knee motion. *Med Sci Sports Exerc.* 2002 2002;34(5).

Hewett TE, Myer GD, Ford KR. The influence of growth and pubertal maturation on neuromuscular performance in high-risk female athletes. *Med Sci Sports Exerc.* 2002 2002;34(5).

Myer GD, Ford KR, Hewett TE. A comparison of medial knee motion in basketball players when performing a basketball rebound. *Med Sci Sports Exerc.* 2002 2002;34(5).

Brodsky JW, Beischer A, Robinson A, Westra S, Negrine JP, Ford K. Hallux Valgus Correction with Modified McBride Bunionectomy and Proximal Crescentic Osteotomy: Clinical, Radiological and Pedobarographic Outcome. Paper presented at: American Orthopaedic Foot and Ankle Society / AAOS Specialty Day., 2001; San Francisco, California.

Wuderlich RE, Ford KR. Plantar pressure distribution during bipedal and quadrupedal walking in the chimpanzee *(Pan troglodytes)*. . Paper presented at: EMED Scientific Meeting, 2000; Brisbane, Australia.

Ford K, Kernozek T. In Shoe Force Distribution Variations and Sensor Characteristics During Distance Running. *Clin Biomech (Bristol, Avon).* 1999 1999;14:554.

Ford K, Stern J, C. M. In-skate pressure distribution differences with a custom molded orthotic. Paper presented at: 4th International Society of Biomechanics Symposium on Footwear Biomechanics, 1999.

Goodwin DA, Ford K. Variable effect of on-snow ski boot pressure measurements: validation of input data for estimating real-time ski pressure distribution. *Knee Surg Sports Traumatol Arthrosc.* 1999;7:388.