2006

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Introduction

The last few decades and the implementation of Title IX have brought about a significant increase in female athletic participation. Title IX was passed in 1972, as part of the Educational Amendment Act, to close the gender gap in athletic opportunities associated with educational establishments.[1-4] Paralleling the rise in participation at the high school and college level has been an increase in the number of injuries sustained by female athletes.[2-5] Since research and records documenting female athletic participation and injuries were virtually non-existent prior to the passing of Title IX and the subsequent flux in female athletes, there is little information to provide answers as to why the female athlete is sustaining injuries at a much greater rate then their male counterpart. Recently, a great deal of attention has been placed on the female athlete and the factors that may contribute to the disparity in injury rates.[2-12]

Certain injuries have been reported to occur at a much higher rate in female athletes than in males. Specifically, this discrepancy in injury rates between males and females is seen at the knee involving the anterior cruciate ligament (ACL)[2-3,10,13] The ACL is an important component in knee stabilization. It attaches to the tibia of the lower leg and to the inner surface of the lateral femoral condyle in the thigh, crossing the knee joint diagonally. This ligament stabilizes the knee by preventing the femur from moving posteriorly on the tibia and limiting excessive tibial internal rotation. In addition to the ligaments providing stability to the knee joint, the surrounding muscles also contribute to minimizing unwanted motion at the joint. Hamstring muscle activation aids in stabilization of the knee joint. A muscular strength imbalance—whether caused by weak hamstrings or by strong quadriceps—thereby hinders stabilization of the knee joint, requiring the ACL to play a larger role in knee stabilization.

The incidence of female ACL tears in sports such as soccer and basketball is much higher than in male athletes competing in the same sports.[2-4,6-8,12,14-16] The role that the ACL plays in the stability of the knee joint is particularly important in sports involving the jump-landing, such as basketball, soccer, and volleyball.[4,16]

Although high rates of ACL injuries are seen in contact sports, the majority of injuries occur as a result of a no contact mechanism. The mechanism causing this injury usually falls into one of three categories: planting and cutting, straight knee landing, and one-step stop landing with the knee in hyperextension.[4,8] Depending on the specific parameters of the group assessed, female athletes are two to eight times more likely to tear the ACL in one of these motions than are male athletes.[2-4,12] Numerous studies focusing on different sports at various levels have shown similar trends, demanding that attention be paid to determining the cause of the female athlete's vulnerability to this injury.[1,6-8,15] Therefore, the purpose of this study was to determine if differences existed in hamstring and quadriceps strength ratios between males and females.

Review of Literature

The increased incidence of no contact ACL injuries reported to occur in female athletes as compared to males clearly indicates a factor (or combination of factors) associated with gender, as a cause for this injury rate discrepancy. Many factors are suggested to be possible contributors, though the exact cause, or causes, has yet to be determined. These factors are most efficiently divided into intrinsic and extrinsic factors.

Intrinsic Factors

Intrinsic factors are those which are not modifiable, and are characteristic of the athlete—not the athlete's movements. These factors that have been suggested to contribute to ACL vulnerability in females include joint laxity, hormonal influences and structural differences. Females are thought to have increased joint laxity as compared to men. Increased laxity and decreased stiffness at the glenohumeral joint have been reported in female athletes who perform overhead motions.[5] This pattern is thought to represent joints of females in general—not only at the glenohumeral joint—which would suggest that females might have greater laxity in the knee joint.

The relationship between hormones and injury has also been investigated. Arendt et al[3] collected self-reported information (regarding menstrual cycle phase) from 38 female athletes who sustained a no contact ACL injury. They found that females were more likely to injure their ACLs just preceding (follicular phase) or just following (luteal phase) their menses. Because of the fluctuation of hormone levels that occur during the menstrual cycle, some researchers have examined these levels (i.e. estrogen) and its relationship to ligament laxity.[17] As a result of this ligament laxity, the neuromuscular control of the joint is compromised, and the position of the knee upon landing is less stable.[18] Hoffman et al[19] examined the relationship between ligament laxity and hormone levels (estrogen and progesterone) in female subjects with regular menstrual cycles and compared these values to a male control group. The investigators concluded that there was no link between hormone level and knee joint laxity.[19] Perrin et al[20] also tested hormones levels (estradiol, progesterone, and testosterone) daily and measured knee joint laxity in 22 females. The results of this study showed that the absolute minimum hormone level—rather than the magnitude of increase or decrease—might correlate with knee joint laxity.

Arnold et al[21] examined the relationship between serum relaxin levels and anterior tibial translation (knee laxity) in 57 collegiate women (athletes-injured/uninjured and non-athletes) and 5 males (controls). The results showed little variance in relaxin levels across gender, though the levels varied greatly in females from week to week. There was increased laxity in females as compared to males, and even more laxity in those females with prior injury, but these trends could not be directly associated with relaxin levels. Wojtys et al[22] studied the relationship between menstrual cycle phase and injury and reported statistically significant results showing that more ACL injuries occurred during the ovulatory phase, and less during the follicular phase of the menstrual cycle. Since studies have produced conflicting results, this factor has not been clearly identified as one that may contribute to the female ACL problem.

Other intrinsic factors that have been considered to be possible contributors to ACL injury include the actual size of the ACL, the size and shape of the intercondylar notch, and lower leg alignment.[17] Research examining these factors is inconclusive as to their role in predisposing one to ACL injury. These are classified as structural factors, and are clearly not modifiable.

Extrinsic Factors

Extrinsic factors are considered to be those that have the potential to be modified or altered by training. Examining these modifiable factors is more productive in dealing with this epidemic of ACL injuries affecting female athletes, since direct pursuit of resolution is possible. Contributing extrinsic factors to the prevalence of ACL injuries in female athletes are jumping or landing characteristics, muscular strength and muscular activation patterns, and skill level.[3,6,8] Skill level is a factor thought less likely to be responsible for the increased ACL injury rate in females.[3,7] Arendt et al[3] found that patterns of injury rate which they assessed from 1994-1998 were similar to those recorded from 1989-1993, ruling out skill level and experience as primary factors for the variance across gender. Although the role of these factors in ACL injury is not conclusive, footwear and playing surface have been studied.

Jumping/Landing Characteristics

Measurements of the forces absorbed by the body in jumping activities are recorded at anywhere from three to 14 times the body weight. This is an incredible amount of stress, which the lower extremity of the body can normally endure. If the positioning of the body in the landing is altered, however, injury can occur. During cutting maneuvers women use less knee flexion, more knee valgus, and less hip flexion than their male counterparts. Also, females have higher quadriceps activation and lower hamstrings activation than males—this variance is more pronounced at footstrike.[6,14,23] The combination of this muscle activation and decreased knee flexion results in increased stress on the ACL.

Hass et al[14] observed differences in landing between prepubescent and postpubescent male and female subjects with the intent to determine when in the maturation process the neuromuscular differences develop. They found differences in strength and neuromuscular control during the landing between prepubescent and postpubecent athletes. They also suggested that muscular training programs should take these differences into account and be individualized to the athlete to prevent ACL injury.

As mentioned previously, ACL injuries occur during landing from a jump. Chappell et al[12] analyzed the anterior shear force on the tibia resulting from stop-jump task in male and female athletes. Each subject performed forward, vertical, and backward jumps, during which the knee extension moment and knee valgus moment were measured. They found that female athletes had a larger shear force on the tibia, which can increase strain on the ACL. Also, during backwards jumps males had varus moments at the knee where females had contrasting valgus moments, again increasing strain on the ACL. The factors responsible for the increased shear force acting on the tibia are suggested to be increased quadriceps force, decreased hamstrings force, a decreased knee flexion angle, or a combination therein.[12,23]

Kinematic differences between males and females during a landing task were identified as possible contributing factors as well.[17,23-30] Decker et al[24] found that females land in a more erect position (less knee flexion) when compared to males. This position places increased stress on the ACL, whereas increased knee flexion may allow the force to dissipate over time. They also found that males reached a peak extensor moment in 0.038 seconds after contact with the ground was made, whereas women reached their peak in 0.063 seconds.[24] To create conditions that closely replicate a common mechanism of injury to the ACL, the landing mechanics that result from drop jumps from unknown heights have been studied. Again, landing strategies differed between gender, as females demonstrated a stiffer position.[23,25,27,28]

Zeller et al[30] examined differences in kinematic and electromyographic activity between males and females during a single-legged squat. Females were found to have significantly increased ankle dorsiflexion, ankle pronation, hip adduction, hip flexion, hip external rotation and decreased lateral trunk flexion as compared to men. They noted that during the single-legged squat females demonstrated an initial "loss of control" characterized by a valgus position of the knee and increased hip adduction and foot pronation. The single-legged squat was deemed indicative of landing style for the purposes of this study.[30]

Habu et al[25] investigated the role of fatigue during a landing task and found that males and females had decreased knee flexion after fatigue. Since females have less knee flexion upon landing than males already, fatigue increases the likelihood of being in a position that can stress the ACL.

Muscular Strength/ Activation Patterns

Strength of the thigh muscles is a critical component in knee stabilization, and it has been shown that women are weaker than males after normalization for body weight.[6] It is also believed that females have a lower muscular endurance than males, so they are sooner fatigued, and therefore vulnerable to injury.[8,25] Elite athletes in sports like soccer, volleyball, and basketball are more likely to hypertrophy their quadriceps. This strengthening may cause the quadriceps to produce a force larger than that tolerated by the ligament, thus injuring it. Adequate hamstring strength to counteract the increased quadriceps activity is important to stabilize the knee joint.

Kulas et al[26] studied the knee extensor reflex during a perturbation and examined the response of the hamstring and quadriceps muscles in ten males and ten females. They reported that females demonstrated a more sensitive reflex and responded to the perturbation with increased quadriceps activation relative to hamstring activation.

Buchanan and Vardaxis[31] compared the knee strength of two groups (ages 11-13, 15-17) of male and female basketball players. Girls aged 11-13 showed similar relative quadriceps strength to girls aged 15-17. When the male groups were compared, however, there was a 60% increase from those ages 11-13, to those ages 15-17. Gender differences in peak torque values across velocities have been reported. [32] Males demonstrated greater concentric and eccentric mechanomyographic responses during isokinetic exercise than females.[32] The authors suggested that this measurement might be affected by general muscle mass or adipose tissue thickness, both factors which may vary across gender.

Hakkinen[33] studied the force production of muscle groups involved in jumping and landing tasks. Males demonstrated higher forces in leg extensor, trunk flexor and trunk extensor muscles, even when normalized for body weight. The study also noted males were able to produce such forces more quickly than females.[33] Whether these differences were inherent or were directly related to training philosophies was not determined.

Davis and Ireland[8] outlined some key ideas critical to understanding the ACL injuries most often sustained by female athletes. They stated that as female athletes anticipate landing, they fired their muscles sooner than males, and relied on the quadriceps in knee stabilization. Anterior tibial translation (ATT) is increased if the quadriceps fire without the hamstrings, requiring the ACL to compensate in stabilization.[34] Female athletes, then, are increasing ATT (resulting in increased stress to the ACL) by using their quadriceps predominantly. The male counterparts and female controls depended more on the hamstrings, or the quadriceps and hamstrings in conjunction. Elite athletes showed this quadriceps-dominant pattern more than non-athletes. These differences in activation patterns cause various structures of the knee to withstand additional force or stress. Training programs to strengthen the hamstrings are thought to increase coactivation of the hamstrings with the quadriceps, removing some of the stress on the ACL, thereby preventing injury.[6,34]

Coactivation of the quadriceps and hamstrings is critical in providing the muscular stability of the knee. When working efficiently, this partnership counteracts ATT, sharing the job with the ACL. If this coactivation is not synchronized or coordinated, the ACL must endure the entire strain, increasing the risk of rupture.[4,34] White et al[4] in discussion of their findings, emphasized the importance of the relationship between the quadriceps and hamstrings, and in the interaction of this musculature with the knee. They suggested that the success of coactivation plays a large role in providing stability to the knee and supporting the ACL in counteraction of ATT. Therefore, it is important to have a balance in strength of the thigh muscles groups in order to provide the necessary stabilization during sport specific activities. DeMorat et al[35] simplified the relationship further, concluding that no contact ACL injuries occur as a result of the ACL being strained under excessive ATT. In many cases this excess strain resulted from a strong quadriceps contraction with slight knee flexion.

In keeping with this philosophy, Yanagawa[36] stated that sufficient coactivation of the hamstrings is necessary to knee stabilization, regardless of the speed of knee extension. The level of co-contraction required, though, is inversely related to the extension speed (in this study, peak ATT decreased as extension speed increased, thus requiring lower levels of co-contraction).[36] It is important to address the question of whether or not females demonstrate a significant difference in their hamstring strength to quadriceps strength ratio. Conceptual differentiation between muscular activation pattern and actual strength ratio is vital. Equally important is the consideration as to whether or not these results implicate this ratio as a contributing factor to the discrepancy of ACL injury rates across gender.

Hamstring: Quadriceps Strength Ratios

To measure and analyze the strength of the thigh muscles and thus the imbalance that may cause ACL injury, a hamstring to quadriceps ratio (H:Q) is used.[34,38-41] Aagard et al[34], for instance, analyzed isokinetic H:Q strength ratios by measuring the peak torque of subjects at various degrees of knee flexion. Although they were unable to provide clear evidence of the role of this muscular imbalance as the culprit in ACL injury, implications have sparked further study. Studies analyzed isokinetic strength ratios in many different conditions, varying between eccentric and concentric contractions and between many angular velocities.[32,34,37] The most functional ratio would be those that are determined by eccentric and concentric contractions of reciprocal muscle groups. It is this ratio that would best replicate what occurs during activity.

Training

Implementation of training programs as a preventative measure of ACL injury has also been considered. Amato et al[42] analyzed the effect age has on isokinetic muscle strength, finding that older athletes demonstrated improved absolute strength over that of younger athletes. This may indicate that training or experience play a role in preventing an athlete from injuring their ACL. It is thought then, that preventative programs should be implemented in younger populations to target the problem before it becomes instilled in the athlete. One program suggested would teach children how to jump and how to land; it would focus on body positioning and muscle firing.[43] Training programs to rehabilitate previously injured ACLs must consider many of the same factors as those programs aimed at its prevention. Gender differences on neuromuscular control encompass most of these factors.[44]

Cerulli et al[45] tested techniques to sharpen the athlete’s proprioception, thus allowing them to react more quickly and more effectively to changes. If this reaction and adaptation can be achieved, the athlete will be able to keep their body in a more stable position, decreasing the likelihood of injury. Varied balance boards were used to simulate different situations, forcing the athlete to react. Proprioceptive neuromuscular facilitation exercises were also used in this training program. Plyometric training has become a focus in prevention programs.[15,46] Improved adductor and abductor coactivation as a result of plyometric training resulted in Chimera’s study, allowing her to conclude that this change can be learned. She also considered that this specific improvement in muscle activation pattern may put the lower extremity in a more stable position to absorb the forces from deceleration, dissipating some of that force from the knee joint[15]. Wilkerson et al[46] studied a specific plyometric-based prevention program its effect on the neuromuscular performance of female collegiate basketball players. Plyometric exercise allowed athletes to improve isokinetic hamstring performance in open chain activity, though closed chain activity produced no significant result.[46]

Ageburg et al[47] evaluated the effect of training programs on subjects after ACL injury and found that supervised training programs assisted in functional performance. Unsupervised programs, however, were unsuccessful. A link between rehabilitative procedure and preventative training programs has not been made determinately, so identification of the causal factor in ACL injury remains the missing piece in creating effective preventative programs. The effectiveness of these preventative programs lies in wait for more evidence to surface regarding the causative factors affecting the incidence of female ACL injuries. At that point more specific preventative training programs can be implemented to directly decrease the number of ACL injuries plaguing female athletes.

Methods

Subjects

Twenty college-aged students (10 males and 10 females) were recruited for this study. Age, height and weight of each subject were recorded (Table 1). Subjects had no previous history of injury to the dominant leg. Dominance was defined as the preferred leg to kick a ball. Prior to participation, all subjects read and signed the informed consent agreement that was approved by the university’s institutional review board.

	Age (years)	**Height (cm)**	**Weight (kg)**
Male	22.1 ± 1.6	175.5 ± 5.8	82.0 ± 10.7
Female	21.7 ± 1.2	163.8 ± 7.1	62.5 ± 9.5

Table 1. Subject Demographics

Test Protocol and Instrumentation

Isokinetic strength measurements of the quadriceps and hamstrings were obtained from a Biodex System 3 (Biodex Medical Systems, Inc.- Shirley, New York) isokinetic dynamometer. We measured peak torque of both muscles concentrically and eccentrically. Testing was conducted at 60°/sec and 180°/sec with the order randomized via a coin-flip to minimize any learning effect.

Subjects were secured to the testing device with criss-cross straps across the torso, a strap across the waist, and a strap across the thigh, and subjects were instructed to cross their arms over their chest. The axis of rotation of the dynamometer was visually aligned with the lateral femoral condyle and the lower leg was strapped to the dynamometer arm with the inferior border of the pad sitting two finger widths above the lateral malleolus.

Each limb was weighed to correct for the effect of gravity on torque measures. This procedure was completed with the subject's leg positioned at or near complete extension.[48] Range of motion for testing was 10°-90°. Subjects performed three submaximal contractions at each velocity to become familiar with the exercise. A two-minute rest was given before the start of the actual test session. Each subject performed three maximal contractions at each speed (with a one minute rest between speeds) for knee flexion and extension. After testing, peak torque values were recorded and normalized for body mass. The peak torque values were used to calculate the ratios. These ratios included the concentric hamstring to eccentric quadriceps ratio and the eccentric hamstring to concentric quadriceps ratio for each speed.

Statistical Analysis

Independent t-tests were used to determine differences in hamstring and quadriceps ratios between males and females at each speed. Peak torque values were used for data analysis, and all values were normalized for body weight. An alpha level of $P<.05$ was set *a priori* for all analyses. For analyses, SPSS 11.0.0 Windows (SPSS, Inc., Chicago, IL) was used.

Results

Independent t-tests revealed a significant difference ($P=.04$) between males and females for the H(ecc): Q(con) ratio@ 60˚/sec. Upon further examination of this ratio, it appears that females had less hamstring strength compared to males. There was no significant difference in the remaining three ratios tested. The ratios are presented in Table 2.

	H(ecc):Q(con)		**H(con):Q(ecc)**	
	60º/sec *	**180º/sec**	**60º/sec**	**180º/sec**
Male	1.10	1.20	0.80	0.72
Female	0.80	1.07	0.77	0.71

Table 2. Strength Ratios (* Significantly different at P<.05)

Discussion

The purpose of our study was to examine the functional H:Q ratios in healthy males and females. Hamstring to quadriceps (H:Q) strength ratios are used to describe the strength surrounding the knee joint. Functional H:Q ratio is an important concept to understand if studies are to provide applicable information.[34,38,39] Aagard et al[34] state that functional H:Q ratios are more effective to describe strength relationships, meaning concentric quadriceps should be compared to eccentric hamstrings—and vice versa—to simulate muscle activation during normal activities. To consider the peak torques of H(con): Q(ecc) is much more functional than H(con): Q(con) or H(ecc): Q(ecc). This makes sense when one considers that these are reciprocal muscle groups, and that the shortening of one results in the lengthening of the other. These functional ratios, then, are more accurate in simulating knee flexion and extension than the traditional ratios.

For our study we decided to use the functional H:Q ratios since they are more effective in identifying where strength discrepancies exist. As mentioned previously, females tend to rely on their quadriceps muscles and have weaker hamstrings. If the quadriceps muscles overpower the hamstrings (which are already weak), the ACL will be stressed. Hamstring activation contributes to knee stabilization, sharing the strain with the ACL and relieving it of sole responsibility.

Thus, training programs that target hamstring strength and activation have been developed, and have demonstrated decreased incidence of injury in females. A functional approach is more applicable to studies relating knee stabilization. Functionally, such results demonstrated that during knee extension, females had stronger quadriceps in relation to hamstrings (or weaker hamstrings in relation to quadriceps) as compared to their male counterparts. To find the specific conditions under which females are most vulnerable to ACL injury would be a truly productive step in solving the problem.

It is important to note that a limitation to our study exists in that our strength ratios were assessed on an isokinetic dynamometer, making it an open kinetic chain exercise. This is not as functional as a weight-bearing, closed kinetic chain exercise would be, were it possible. Under perfect conditions, the speeds tested would also be functional to those performed during athletic activities. We are implying that the muscle will act in the same manner during the isokinetic testing, as we would see during functional or sport-specific activity.

Conclusion

Our study found significant differences between males and females in H(ecc): Q(con) ratio @ 60˚/s, indicating a larger difference in muscle strength. No significant difference resulted in H(con):Q(ecc) ratio @60˚, nor in either ratios at 180˚/s. The functional application of this indicates a quadriceps-dominant muscular imbalance for females under some conditions. Muscular imbalance and muscular activation patterns affect stabilization of the knee. If muscular stabilization is insufficient, ligamentous integrity is compromised. Thus if muscular stabilization surrounding the knee is improved, vulnerability of the ligaments about the knee, especially the ACL, is decreased. This is certainly pertinent when developing training programs to strengthen knee stabilizers and protect the female ACL.

Future research, however, is required to establish whether or not a clear cause-effect relationship exists between strength ratios and ACL injury. Functional ratios should continue to be reported in the literature. If such a relationship is identified, then further study to fine-tune muscular and biomechanical training programs needs to be implemented to address specific deficits in strength ratios of female athletes.

Acknowledgement

This project was made possible by the direction, patience, and guidance of Dr. Bernadette Buckley of the University of North Florida (UNF) Department of Athletic Training and Physical Therapy; the instruction of LouAnne Hawkins of the UNF Honors Program; and the funding by the UNF Undergraduate Research Award from the Undergraduate Academic Enrichment Program, directed by Dr. Mary O. Borg.

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