Hamstring and Quadriceps Strength Ratio in Collegiate Wrestlers

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Abstract

ACL injuries are a significant risk for athletes across sports. One of the sports that reports the highest rate of ACL injury is wrestling. The mechanism of injury among wrestlers appears to be unique and has limited data compared to other sports. Several nonmodifiable risk factors have been studied for ACL injury, as well as several modifiable risk factors that include BMI, muscular composition, and high-risk movements. The hamstring to quadriceps strength ratio (H:Q) is one aspect of muscular composition that has received little attention in collegiate wrestlers. The purpose of this study was to analyze the H:Q strength ratio in male collegiate wrestlers in order to investigate the ACL injury risk in this population.

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Introduction

Anterior cruciate ligament (ACL) injuries present a major risk for many athletes, and much effort has been given to reduce the risk of these injuries (Shultz et al., 2019). Part of this approach has been in identifying risk factors for ACL injuries. Many factors influence the onset of ACL injuries and despite current interventions, injury risk remains high (Shultz et al., 2019). Further research is needed to mitigate the risk of ACL injuries across different sports.

For men, the sports that have the highest incidence of ACL injuries are football, with an injury rate of 0.17 injuries per 1000 athlete-exposures (A-Es) and wrestling, with an average ACL injury rate of between 0.15 and 0.16 injuries per 1000 A-Es (Agel et al., 2016). Other men's sports include basketball (0.08), lacrosse (0.13), and soccer (0.04). Women's sports record even higher rates. This includes women's basketball (0.22), gymnastics (0.24), field hockey (0.11), soccer (0.10), and volleyball (0.04).

Wrestling has one of the highest rates of ACL injuries in male sports (Agel et al., 2016). However, little is known about rate of contact ACL injury in the sport. Since wrestlers are generally in contact with each other during practice or competition, a "contact" injury for the purposes of this study will be considered direct contact to the knee joint. An analysis of ACL injuries in sumo wrestlers revealed some of the potential injury mechanisms for wrestlers (Goshima et al., 2011). While sumo wrestling is a sport distinct from collegiate wrestling, it still is a grappling-based sport, and thus is worth considering (Beekley et al., 2006). This study reported a noncontact injury rate of 100 percent for the 8 wrestlers who were analyzed in this study (Goshima et al., 2011). Another study looking at collegiate wrestlers reported a noncontact injury rate of 50 percent (Lightfoot et al., 2005).

Mechanism of ACL Injury Across Sports

The mechanism of ACL injury has been studied in depth in several sports, and usually occurs while changing direction in non-contact situations (Waldén et al., 2015). Single leg "cutting," or changing direction at high speeds, shows little activation of the hamstring and greater activation of the quadriceps, which could increase the strain on the ACL (Colby et al., 2000). Landing from a jump can also lead to ACL injury, such as in skiing (Hame et al., 2002). These movements lead to anterior shear force on the tibia or a torsion force within the knee, which significantly increases stress in the ACL (Meyer & Haut, 2008). This mechanism of noncontact injury is commonly reported across multiple sports, including soccer and basketball (Krosshaug et al., 2007; Waldén et al., 2015). Among wrestlers, however, the mechanism of injury is not well understood. In sumo wrestlers, ACL injuries have been found to occur when a planted leg is externally rotated and flexed at a mean angle of 57.2 degrees (Goshima et al., 2011). Another study supported these findings, as ACL injury occurred when a planted foot was twisted with subsequent rotation of the knee joint, or when there was direct contact to the knee (Lightfoot et al., 2005). This study by Lightfoot et al. is the only study to date that has analyzed the mechanism of ACL injury in collegiate wrestlers.

Nonmodifiable Risk Factors

Gender

Much higher ACL injury rates have been reported in female athletes than in male athletes (Uhorchak et al., 2003). Female soccer players are at least three times more likely to suffer ACL tears than male soccer players (Agel et al., 2005), and female basketball players are four times more likely to suffer an ACL injury compared to their male counterparts (Arendt & Dick, 1995). Interestingly, the common risk factors identified for ACL injury appear to predict injury more accurately for women than men (Uhorchak et al., 2003). In a prospective 4-year study of 859 military cadets, ACL injury was compared to several risk factors, and it was determined that the non-contact injuries among men were much more random and less related to significant risk factors, suggesting different noncontact injury mechanisms (Uhorchak et al., 2003). Several studies analyzing the anatomy and function of male and female knee joints support this notion. One study performed stress testing on the knee by introducing an anterior translation stress on the tibia with 30 pounds of force (Huston & Wojtys, 1996). In this study, females recorded the greatest tibial translation among both athlete and control groups, indicating greater joint laxity. Additionally, female athletes recorded a different muscular activation than the other groups: they contracted their quadriceps first in response to the stress, whereas the other groups (male control, female control, and male athletes) contracted their hamstrings first. This suggests less antagonistic contraction from the hamstring to support the ACL. Men are also able to produce significantly greater peak torque than women, including when adjustments for bodyweight are made (Anderson et al., 2001), and men also have been reported to have greater H:Q ratio at 60 deg · sec^{-1} of flexion and extension of the knee (Anderson et al., 2001).

Notch Width

Notch width may be a factor predisposing ACL injury. Femoral notch width is measured at the level of the popliteal groove and is the distance between the inside of the femoral condyles (Muneta et al., 1997). A joint notch less than 13 mm among women is considered narrow and may be related to ACL injury (Uhorchak et al., 2003). However, the evidence for whether joint notch width is related to ACL injury is conflicting (Schickendantz & Weiker, 1993, Keays et al., 2016). A study by Lombardo et al. (2005) did not support a narrow notch as a risk factor for ACL injury. However, this was for professional male athletes with an average notch width of 23 mm. Only 2% of participants had a notch width less than 15 mm. This is still significantly larger than the 13mm that was considered a risk factor for females and should be taken into consideration. Notch shape and geometry has also been considered a possible contributor. Five unique shapes for the notch have been identified, suggesting more factors than simple notch width (Anderson et al., 1987). Simon et al. (2010) supported this idea by measuring the intercondylar notch inlet and outlet and found that both were significantly larger among the healthy group in this study as compared to the group that suffered ACL injury.

Joint Laxity

There is conflicting evidence regarding the relationship between joint laxity and ACL injury. Joint laxity has been shown to be present among those with previous ACL injury (Branch et al., 2010). Among women in particular, joint laxity may increase their risk of ACL injury. A five times greater risk for ACL injury among female athletes has been indicated for those with a positive test for knee hyperextension (Myer et al., 2008). This joint laxity among women may occur due to hormonal differences. Shultz et al. (2012) found that the landing biomechanics among women was worst during the point in their menstrual cycle of greatest joint laxity, which is associated with the greatest change in estrogen levels (Heitz et al., 1999). There is also potential evidence for variations in tendon strength from the menstrual cycle, though there is little agreement in this area (Hughes & Watkins, 2006; Wojtys et al., 2002). A study by Weesner et al. (2016), however, reported no significant difference between male and female joint laxity when tested with an arthrometer when testing at 30 degrees and 70 degrees of flexion, thus calling the influence of gender on joint laxity into question. When considering both genders, a statistically significant difference has been found but may not be truly significant due to high standard deviation in the results (Anderson et al., 1987). Thus, there is conflicting evidence regarding joint laxity as a risk factor for ACL injury.

Ligament Thickness

Despite no direct connection to ACL injury, there are other potential markers of a relationship between ligament thickness and ACL integrity. According to Hughes & Watkins (2006), there is no evidence of a connection between ACL thickness and rate of injury. However, indirect indicators have been suggested through several avenues. Differences between male and female ACL size have been demonstrated, suggesting weaker ACL structures among women (Charlton et al., 2002). Intercondylar notch width and volume, which has a more established relationship with ACL injury, has evidence for a correlation with ACL volume (Simon et al., 2010). While not a direct connection, Chaudhari et al. (2009) found a significant relationship between ACL size and injury when controlling for weight in the individual. They found that the ACL volume was 231mm^2 less than the non-injured ACL on average when controlling for weight. Quadricep strength is another factor that may be correlated with ACL thickness, suggesting that ACL volume is increased as an adaptation from the stress from greater quadricep activation. These results suggest an indirect connection between ACL volume and injury.

Patellar Tendon-Tibia Shaft Angle

There is some evidence supporting the patellar tendon-tibial shaft angle (PTTSA) as a risk factor for ACL injury. The PTTSA represents the angle between the line of action of the patellar tendon and the tibial shaft (Hughes & Watkins, 2006). A larger measure of this angle indicates greater shear force on the tibia, which leads to greater strain on the ACL. The strain on the ACL has been measured to be the greatest at or near full extension of the knee (Hughes & Watkins, 2006). Nunley et al. (2003) found that there was a linear relationship between the knee angle and the PTTSA, so that the PTTSA increases as the knee extends. This study also reported that women had an average of 3.7 degrees greater PTTSA than males and 13.2% greater shear force, suggesting greater PTTSA forces among women. Figure 1 illustrates the line of action for the force created by the PTTSA.

Q-Angle

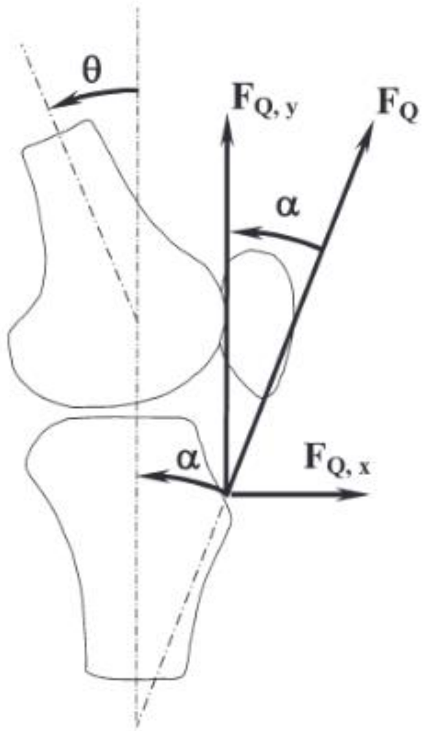
There is limited data in regard to the effect of Q-angle on ACL injury. Gender differences have been documented, with females recording a 30% greater Q-angle than males (Moul, 1998). While general ACL injuries do not suggest a significant relationship with the Q-angle, there is evidence that supports a significant difference among non-contact ACL injuries (Kızılgöz et al., 2018; Mohamed et al., 2012). Thus, the data is limited in regard to the effect of Q-angle on ACL integrity.

Posterior Tibial Slope

The posterior tibial slope has been studied in relation to the ACL, as an increased angle may increase the strain on the ACL. The mechanism of stress comes from the force directed downward on the tibia from landing on the leg, which is redirected as an anterior shear force due

Figure 1

PTTSA Force Line of Action



Note: Nunley, R. M., Wright, D., Renner, J. B., Yu, B., & Jr, W. E. G. (2003). Gender comparison of patellar tendon tibial shaft angle with weight bearing. *Research in Sports Medicine: An International Journal*, *11*(3), 173–185. https://doi.org/10.1080/15438620390231193. Used with permission from Taylor and Francis Online.

to the posterior tibial slope (Bojicic et al., 2017). It has been demonstrated that trauma-based impact may lead to greater injury among those with greater posterior tibial slope (McLean et al., 2011). As little as a 1 degree reduction in posterior tibial slope may indicate an 11 percent increase in the risk of ACL injury (Bojicic et al., 2017). Lateral posterior slope specifically has support as a risk factor as well. The lateral posterior slope causes rotation of the femur in relation to the tibia, since the lateral posterior slope causes rotation when under axial compression (Simon et al., 2010). A significant relationship between injury and greater lateral posterior slope has also been reported by Simon et al. (2010). Thus, an increase in posterior tibial slope may be related to a greater ACL injury risk.

Model for Passive Stability

A model for passive stability of the knee joint has been proposed by Hughes and Watkins (2006). This model incorporates several of the non-modifiable risk factors and is presented in Figure 2. This model presents a potential organizational model for ACL integrity. The "size and shape of the condylar surfaces" incorporates the notch width in its definition, which has been discussed as a risk factor for ACL injury (Hughes & Watkins, 2006, p. 416). Also mentioned is the ligamentous cross-sectional area, which would include the ACL itself. Lastly, the ligament laxity, which may be caused by several factors, has been discussed as a potential risk factor. Thus, this model presents a possible framework for ACL integrity regarding the passive structures of the knee.

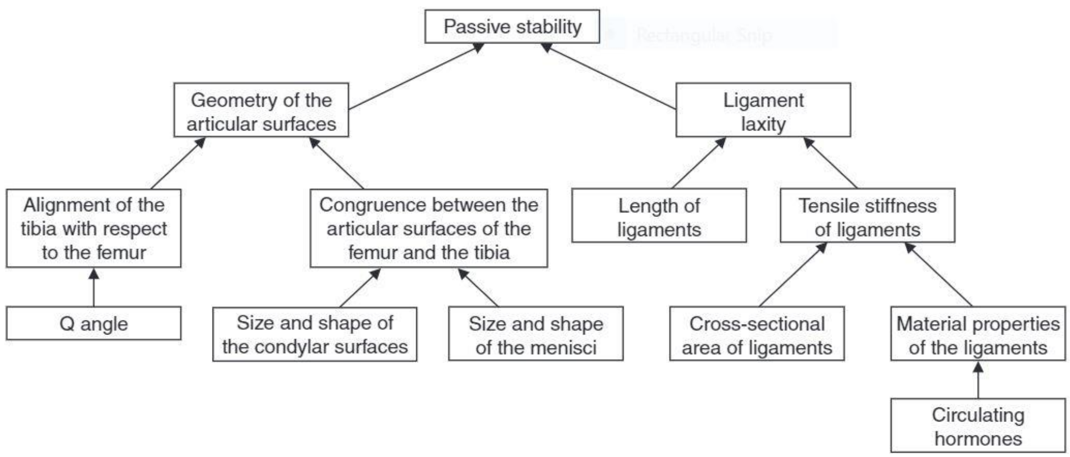
Modifiable Risk Factors

Body Mass Index (BMI)

A higher body mass index has evidence as a risk factor for ACL injury, particularly when present with other risk factors. Uhorchak et al. (2003) indicated that a higher BMI has been indicated as a risk factor for ACL injury, especially among women. They found that females greater than 1 SD above the mean BMI were at a 3.5 times greater risk of ACL injury. However,

Figure 2

Model for Passive Stability within the Knee Joint



Note: Hughes, G., & Watkins, J. (2006). A risk-factor model for anterior cruciate ligament injury. *Sports Medicine*, *36*(5), 411–428. https://doi.org/10.2165/00007256-200636050-00004. Used with permission from Springer Link.

there was not a connection between BMI and ACL injury among the men in this study. Anderson et al. (2001) also supports the influence of gender on the effect of BMI. They found that men had a greater ACL cross-sectional area than women at the same bodyweight based on MRI scans. However, when correcting for lean body mass, there was no significant difference between ACL size for male and female. This potentially explains why a greater BMI appears to be more of a risk factor for women than for men.

A study of 1687 naval academy students showed that a narrow notch combined with an increased BMI showed a significant relationship with ACL tears (Evans et al., 2012). It was also noted that the mean BMI of the injured group was 25.6 kg · m^{-2}, and the BMI of the uninjured group was 24.4 kg · m^{-2}. There is also evidence for a relationship when considering both genders. ACL injury risk has also been supported for BMI in combination with posterior tibial slope (Bojicic et al., 2017). In addition, a greater bodyfat to lean muscle ratio has been associated with a greater knee valgus during a single-leg jump landing (Akimoto et al., 2009). Based on these findings, BMI has evidence that supports it as a risk factor for ACL injury.

High-Risk Movement

Several positions and movement patterns have been identified as potentially influential on ACL injury. One is the valgus knee position (Colby et al., 2000; Kim et al., 2015; Shin et al., 2009). It has been reported that ACL strain is greater when landing in a valgus position than when landing in a neutral position (Shin et al., 2009). With a valgus moment between 0 and 8 Nm, Shin et al. (2009) reported a negligible measurable increase in ACL strain. When the valgus moment was between 10 and 40 Nm, however, there was a greater increase in ACL strain, suggesting a greater risk of injury when the knee valgus is apparent. However, researchers have noted that an isolated valgus moment does not appear sufficient to cause an ACL tear. Significant levels of valgus orientation and internal tibial rotation have been found among knees with injured ACL's when analyzing MRI scans of the injured knees (Kim et al., 2015; Oh et al., 2012). Knee valgus in combination with internal tibial torque also increases the risk of injury to a greater degree (Oh et al., 2012). Thus, knee valgus may be considered a risk factor for ACL injury.

An additional risk factor associated with body movement is the degree of knee flexion, usually when it is less than 25 degrees (Kim et al., 2015; Quatman et al., 2013; Renström et al., 1986). Kim et al. (2015) reported an average of only 12 degrees of knee flexion in the predicted injury positions from MRI knee scans. Renström et al. (1986) analyzed strain on the ACL using load cells in cadaver knee joints and found that the hamstring has no protective effect on the ACL until knee flexion reaches 30 degrees. Quatman et al. (2013) found that strain is significantly greater in the ACL than in the medial collateral ligament (MCL) at 25 degrees, which demonstrated how ACL tears can occur without concomitant MCL tear during knee valgus injuries.

A different type of motion associated with ACL injury is perturbed or abnormal motion. Haddara et al. (2020) looked at the difference between male and female quadricep and hamstring muscle activation. They looked at this because perturbation during locomotion leading to abnormal movement patterns is a common precedent for non-contact ACL injury (Griffin et al., 2006). The subjects performed the trial on a treadmill and received the perturbation by slowing the treadmill from 1.1 m · sec^{-1} to 0 m · sec^{-1} at a rate of 2.9 m · $sec^{-2.}$ The study results showed that the females had 1.6 times greater quadricep activation during the recovery of the perturbation, which was significantly different than males. The male results reported twice the hamstring activation of the females.

A torsion force on the knee, specifically when resulting from an internal tibial torque, has been associated with greater stress on the ligament, as well as a greater risk of ACL tear at the time of injury (Kim et al., 2015; Oh et al., 2012). This commonly occurs during cutting maneuvers while running but is also the primary noncontact method of injury reported in wrestlers (Lightfoot et al., 2005). In wrestling, however, it is a more significant torsion force, since the injuries described by Lightfoot et al. (2005) and Goshima et al. (2011) are from twisting on a planted foot. It’s notable that the torsion force that most affects the ACL is internal tibial torsion, rather than external tibial torsion. Fleming et al. (2001) analyzed internal tibial forces on the ligaments within the knee in vivo using an arthroscopically applied transducer. Since it was conducted in vivo, it presents a unique perspective compared to in vitro studies. They reported that an internal tibial torsion force of 10 Nm resulted in greater ACL strain, but an equivalent external torsion force resulted in no change to the ACL strain. A strain of 125 Nm on the ACL and MCL has been found elsewhere after receiving a 3 Nm internal tibial torque load (Meyer & Haut, 2008). When the force is increased to 10 Nm, a tensile strain of 230 Nm was found (Hame et al., 2002). When under weightbearing conditions, however, both internal and external torsion force resulted in increased strain on the ACL (Fleming et al., 2001).

Contralateral Muscle Imbalances

There is evidence that contralateral muscle imbalances in the lower limbs indicate a higher risk of injury to the legs. There is a trend toward injury when leg strength varies by more than 15% between each leg (Knapik et al., 1991). Orchard et al. (1997) reported that for Australian footballers, all the hamstring absolute peak torque values were weaker on the side that was eventually injured compared to the uninjured side. Leg dominance has also been studied in relation to ACL injury. Among female athletes, no significance was found between dominant and non-dominant legs as to which one induced greater ACL loading (Mokhtarzadeh et al., 2017). However, the investigators did not analyze the peak torque differences between legs, so there may not have been a significant contralateral strength deficit. In one retrospective study, 74% of males injured their dominant kicking leg, whereas only 32% of females injured their dominant kicking leg (Brophy et al., 2010). Thus, it appears that the non-dominant leg among women, which is likely the weaker leg, is at a greater risk of injury. The mechanism among men is less clearly understood than that among women, as discussed earlier (Uhorchak et al., 2003). Other researchers have reported no significant difference for the dominant leg versus the non-dominant leg as an indicator for ACL injury, but it is not clear whether their statistical analysis was performed on genders individually (Negrete et al., 2007).

Hamstring to Quadriceps Strength Ratio

The hamstring to quadriceps strength (H:Q) ratio has been studied as a risk factor for ACL injury (Orchard et al., 1997; Weinhandl et al., 2014). A low H:Q ratio is thought to increase the risk of an ACL tear. A leg that has a deficient H:Q ratio is said to exhibit "quadriceps dominance" (Ford et al., 2003, p. 1746). The H:Q ratio has been studied as a risk factor for both muscular injury and ACL injury.

H:Q Ratio and ACL injury

Several researchers have analyzed the role of the H:Q ratio in protecting the ACL. Wieschhoff et al. (2017) investigated the ratio between the vastus medialis and semimembranosus quadricep muscles to help determine the role of the hamstring to quadriceps ratio as an indicator for ACL injury (Wieschhoff et al., 2017). MRIs of 100 subjects with complete ACL tears were compared to MRIs of 100 subjects without ACL abnormalities. Since the researchers analyzed both the semimembranosus and vastus medialis from each MRI, there were a total of 400 muscle measurements that were performed. Recognizing the confounding effect of atrophy and swelling, the researchers defined any scan after 14 days of injury as "late" and before 7 days of the injury as "early." The noncontact ACL injury scans revealed a muscle ratio of 1.41, whereas the control displayed a significantly lower ratio of 1.29. The contact ACL injury group showed a ratio of 1.23, while the matched control group showed a ratio of 1.26, which was not significantly different. This supports the idea that the H:Q ratio is a good predictor for noncontact ACL injuries, but not for contact injuries.

Myer et al. (2009) also affirmed the H:Q ratio as a risk factor for ACL injury. They reported that the majority of females who remained healthy were above the ratio of 0.6 with a mean ratio of 0.61, while the majority of females with eventual ACL injury where below the 0.6 strength ratio when tested, with a mean of 0.56. Both Li et al. (1996) and Hohmann et al. (2019) supported this association between a higher H:Q ratio and diminished ACL injury.

Role of the Hamstrings in Protecting the ACL

Numerous investigators have analyzed the effects of the hamstring as a supporting agent for the ACL, providing further support for the H:Q ratio as a risk factor. Renström et al. (1986) analyzed strain on the ACL using load cells in cadaver knee joints and found that the hamstring has a protective effect on the ACL beyond 30 degrees of flexion. The researchers noted that the knee was more stable when the hamstring was close to the strength of the quadriceps, particularly when both the quadriceps and hamstrings had higher absolute strength. Anderson et al. (2001) supports this, finding that individuals with strong quadriceps also had strong hamstrings with $p < .001$. Isometric contraction of the hamstring was also shown to decrease load on the ACL (Renström et al., 1986).

More et al. (1993) measured the effect of the hamstring on anterior tibial translation and ACL load. The researchers used a cadaver knee and a mechanical apparatus to simulate the forces of the quadriceps and hamstring muscles in the knee. They found that the ACL load was decreased significantly when the hamstring was activated compared to when it was not. They noted that the ACL strain was decreased the most during 15-45 degrees of flexion and had a significance of $p = .006$ at 90 N of force from the hamstrings. They also noted that the load on the ACL at full extension was the same with or without muscle activation. This supports the injury mechanism of limited knee extension, as there is little to no hamstring support in that range.

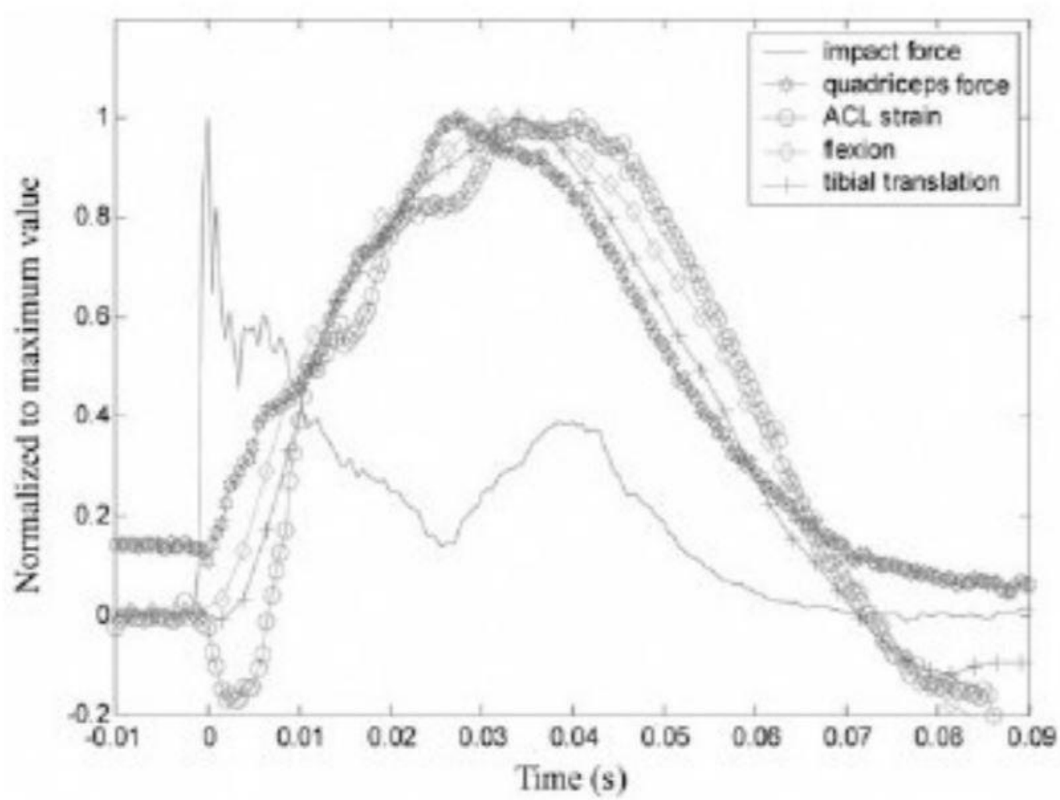
When the forces within the knee are increased, the results are similar. Withrow et al. (2006) intended to learn the effects of the forces from a single leg jump on the ACL, which are much greater than the modest loadings from More et al. (1993). Since Withrow et al. (2006) more closely replicated the forces found in the knee, they more accurately analyzed the injury mechanism. A cadaver knee was used in conjunction with a mechanical apparatus that applied approximately double-bodyweight forces to the knee joint, ranging from 1248 N to 1954 N depending on the trial. The researchers found that the force on the quadriceps strongly correlated with the strain on the ACL, with $p < .00001$. While not extensively discussed by the author, it appeared that the tibial translation was strongly correlated with the ACL strain as well, as shown in Figure 3.

Gender differences in hamstring activation have been identified. Malinzak et al. (2001) tested men and women who performed a running protocol while their hamstring and quadricep muscle activity was monitored. The women were found to have 17-40% greater quadricep activation and up to 20% less hamstring activation than the men in the study. The differences between genders in maximal contraction was accounted for by comparing their contractions while running to their maximal contraction.

Other studies have indirectly investigated the effect of hamstring strength in protecting the ACL. Weinhandl et al. (2014) found that there was an increased ACL load when the

Figure 3

ACL Strain and Other Forces from a Single Leg Jump Simulation



Note: Withrow, T. J., Huston, L. J., Wojtys, E. M., & Ashton-Miller, J. A. (2006). The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. *The American Journal of Sports Medicine*, *34*(2), 269–274. https://doi.org/10.1177/0363546505280906. Used with permission from Sage Journals.

hamstring was fatigued. Bennett et al. (2008), however, did not find a connection between the H:Q strength ratio and anterior tibial shear force, which is an indicator of ACL strain (McLean et al., 2011).

Selection of the Conventional H:Q Ratio of 0.6

Of the investigators that describe the H:Q ratio among different populations, the majority of them determine the ratio of 0.6 as the marker for whether the population is deficient (Bennett et al., 2008; Myer et al., 2009; Orchard et al., 1997). As cited elsewhere, the initial authors to suggest this ratio were Klein and Allman in 1969, who proposed it in order to establish a ratio that would help prevent muscular strains (Balogun, 1987; Dibrezzo et al., 1985). Coombs & Garbutt (2002) stated that the conventional value is 0.6, but also state that this value fails to account for the position of the joint and whether the movement is concentric or eccentric. Grygorowicz, M., Michałowska, M., Walczak, T., Owen, A. et al. (2017) performed a statistical analysis to find what H:Q ratio had both the highest specificity and sensitivity for hamstring strains. A cut-off value of 0.658 was identified, which is close to the conventional value of 0.6. It is also worth noting again that this calculation was for hamstring strains, not ACL injuries. Grygorowicz, M., Michalowska, M., Walczak, T., Grabski, J. et al. (2017) also specifically analyzed the relationship between H:Q ratio and ACL injury. No significant relationship between the H:Q ratio and ACL injury was found, but the value of 0.63 $\pm$ 0.11 was calculated as a cut-off value for H:Q ratio among this population.

H:Q Ratio Population Data in Male Sports

The H:Q strength ratio has been documented among collegiate and professional football players, who have the highest rate of ACL tears in male sports as described earlier (Colby et al., 2000; Tatlıcıoğlu et al., 2019). However, the H:Q ratio among wrestlers has received much less attention, with most literature focusing on populations of freestyle, elite level wrestlers or adolescents (Camic et al., 2010; Polat et al., 2018). Elite wrestlers have been reported to have an average H:Q ratio of 0.63 in their right leg and 0.6 in their left leg, while H:Q ratios in elite football players are between 0.55 and 0.6 bilaterally (Grygorowicz, M., Michałowska, M., Walczak, T., Owen, A. et al., 2017; Polat et al., 2018). Housh et al. (1989) found a ratio of 0.63 among high school wrestlers. Roemmich & Sinning (1997) observed a ratio between 0.56 and 0.63 among adolescent wrestlers depending on the time with respect to the season.

H:Q Data in Collegiate Wrestling

A study describing the general H:Q strength ratio among folkstyle collegiate wrestlers has not been identified at the time of this report. Freestyle wrestling is a style of wrestling that allows for both upper body and lower body attacks in which wrestlers seek to wrestle the opponent into a position of weakness inferior to the wrestler (Yard & Comstock, 2007). Folkstyle wrestling is derived from freestyle wrestling, also including both upper and lower body attacks, but differs in that it emphasizes controlling the opponent after achieving a dominant position (Polat et al., 2018). An analysis of the strength ratio of folkstyle wrestlers would provide more useful information than that of freestyle, due to the greater level of documentation for the rate of ACL injuries among folkstyle wrestlers to compare the H:Q ratio to (Agel et al., 2016; Otero et al., 2017). The purpose of this study was to analyze the H:Q strength ratio in male collegiate wrestlers in order to investigate the ACL injury risk in this population.

Methods

This study utilized a quasi-experimental study design. Five wrestlers from the men's wrestling team at Liberty University in Lynchburg, Virginia participated in this study. Participants were required to be at least 18 years old, be currently on the roster, and not have any musculoskeletal injury or surgery to the lower limbs in the past 6 months. Each wrestler signed a consent form prior to the study, and participation in the research was on a voluntary basis.

After arriving at the testing site, the participants were fitted to the isokinetic machine. Prior to testing, participants were asked their height, weight, age, dominant limb, and years of experience in wrestling. Testing was performed on the Humac2015 NORM isokinetic machine from CSMi, Stoughton, MA. Starting position was set with the tibia perpendicular to the ground and the end position was set with the knee at full extension. Participants were verbally encouraged during the test to maximize performance on the isokinetic machine. The participants first performed 5 submaximal repetitions at 60 degrees per second to warm up. After the 5 submaximal repetitions at 60 degrees per second they rested 10 seconds and performed 5 maximal repetitions at 60 degrees per second. After resting 30 seconds, they performed 5 submaximal repetitions at 180 degrees per second to warm up again. After the 5 submaximal repetitions they rested 10 seconds and then performed 5 maximal repetitions at 180 degrees per second. The machine was then fitted for the other leg, and the same procedure at both speeds was performed.

The first trial served to acclimate the participants to the machine which allowed for participants to produce maximum output. This trial for both legs was repeated a second time. Data were collected only from the second trial. The peak torque H:Q ratios for the left and right leg at both speeds as well as the anthropometric data was analyzed using SPSS software and was expressed as average and standard deviation. The H:Q ratios from the dominant and non-dominant limbs were compared with a paired sample T test to assess whether the H:Q ratios between them were significantly different.

Results

General characteristics of the wrestlers are given in Table 1, and H:Q ratios are given in Table 2. Peak torque values are given in Table 3. The paired samples T test results are shown in Table 4. There was no significant difference in H:Q ratios between dominant and nondominant legs with $p = 0.909$. The non-dominant limbs recorded higher peak torque in every category except for hamstrings at 180 deg · sec^{-1}.

Table 1

Descriptive Characteristics

Variables	**Mean ± SD**
Age (years)	20.4 ± 1.6
Body mass (kg)	93.2 ± 23.6
Height (cm)	178.3 ± 10.5
Wrestling experience (years)	7.6 ± 4.5

Table 2

H:Q Ratio Characteristics

1	**Variables**	**Mean ± SD**
2	H:Q Right leg (60 deg · sec^{-1})	0.787 ± 0.075
3	H:Q Left leg (60 deg · sec^{-1})	0.838 ± 0.069
4	H:Q Right leg (180 deg · sec^{-1})	0.883 ± 0.087
5	H:Q Left leg (180 deg · sec^{-1})	0.914 ± 0.120

Table 3

Peak Torque Characteristics

1	**Variables**	**Mean ± SD**
2	Dominant quadricep (60 deg · sec^{-1})	120.8 ± 29.0
3	Non-dominant quadricep (60 deg · sec^{-1})	122.8 ± 35.0
4	Dominant hamstring (60 deg · sec^{-1})	97.2 ± 20.9
5	Non-dominant hamstring (60 deg · sec^{-1})	100.4 ± 32.0
6	Dominant quadricep (180 deg · sec^{-1})	74.8 ± 20.1
7	Non-dominant quadricep (180 deg · sec^{-1})	79.0 ± 20.6
8	Dominant hamstring (180 deg · sec^{-1})	74.8 ± 18.2
9	Non-dominant hamstring (180 deg · sec^{-1})	71.0 ± 19.6

Table 4

Participant characteristics of comparison groups (mean ± SD)

Peak Torque	DOM	NON-DOM	*p*-value
60 deg · sec^{-1}	0.811 ± 0.044	20.33 ± 1.63	0.909
180 deg · sec^{-1}	0.899 ± 0.074	0.899 ± 0.150	1.000

Note: SD: Standard deviation; DOM: Dominant leg; NON-DOM: Non-dominant leg

Discussion

To the researcher's knowledge, this was the first study reporting on the peak torque values in collegiate wrestlers. The H:Q ratios found in this study were much higher than what was reported in other wrestling studies, ranging from 0.79 to 0.91 (Housh et al., 1989; Polat et al., 2018; Roemmich et al., 1997). This indicates that the participants in this study were not at risk for ACL injury based on the H:Q ratio. While the hamstring values were slightly higher than other studies, the quadricep values appeared to be lower than those found in other studies. The H:Q ratios in this study are also higher than the values found in other sports (Dibrezzo et al., 1985; Grygorowicz, M., Michałowska, M., Walczak, T., Owen, A. et al., 2017; Myer et al., 2009). The nature of wrestling is conducive to increased hamstring strength. Wrestlers move around in a flexed hip hinge position, which places the hamstrings under load (Del Monte et al., 2020). Additionally, wrestling involves many positions with significant knee flexion, which mimics the muscle activation requirements of the squat. Squats require a co-contraction of the hamstrings for stabilization, particularly around 90 degrees of flexion (Jensen & Ebben, 2000). Thus, it would make sense that the H:Q ratio would be higher in the wrestling population.

Contralateral differences in leg strength were minimal among participants. The mean peak torque values were within 5 Nm of each other, though the standard deviations were high. Among collegiate football players, the leg strength discrepancy has been reported to be higher

(Tatlıcıoğlu et al., 2019). Since the leg strength differences were minimal among the participants, this is not a significant risk factor for this sample.

The mechanism of ACL injury is an area that requires further research. Only one study was found documenting the mechanism of ACL injury among folkstyle or freestyle wrestlers (Lightfoot et al., 2005). A common mechanism identified in this study and in the study on sumo wrestling ACL injury was twisting on a planted foot. However, in running sports, the common form of injury is from a large quadricep activation in combination with a valgus moment (Krosshaug et al., 2007). Thus, among wrestlers, the significant stress on the ACL would be rotational, rather than a shear force from quadriceps contraction. This suggests that risk factors related to anterior shear, including the posterior tibial slope and PTTSA, are less effective in predicting future ACL injury among wrestlers. The effect of the H:Q ratio on injury prevention in this population is still unclear, since the hamstrings also contribute to the rotational control of the knee (Jónasson et al., 2016). A recommendation for future studies is to investigate potential risk factors for both shear and rotational stress within the knee, as well as a prospective design to assess whether isokinetic data gathered prior to the wrestling season may be predictive of knee injury over the course of a wrestling season.

One limitation of this study was the small number of participants who volunteered for this study. Due to a large percentage of wrestlers on Liberty’s team with injuries to the lower limbs within the past 6 months, only a few were qualified to participate in the study. Potential sources of error that may account for the above average H:Q ratios include the calibration of equipment, the effect of wrestling training on testing results, the small sample size, or the ROM used for testing.

In conclusion, although study outcomes suggest that wrestlers may have above average H:Q ratios and similar quadricep and hamstring strength, additional research that incorporates much larger sample sizes is necessary in order to validate these conclusions. Similarly, despite the results of the current study indicating wrestlers may not be at an elevated risk for ACL injuries based on H:Q ratio and contralateral strength discrepancy, further investigations utilizing a greater sample size are required to help reveal whether these observed trends exist.

References

Agel, J., Arendt, E. A., & Bershadsky, B. (2005). Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: A 13-year review. *The American Journal of Sports Medicine*, *33*(4), 524–531. https://doi.org/10.1177/0363546504269937

Agel, J., Rockwood, T., & Klossner, D. (2016). Collegiate ACL injury rates across 15 sports. *Clinical Journal of Sport Medicine*, *26*(6), 518–523. https://doi.org/10.1097/jsm.0000000000000290

Akimoto, T., Urabe, Y., Ichiki, Y., & Ide, K. (2009). Relationships between hamstring muscle activation and valgus knee angle in single-leg jump landing. *Rigakuryoho Kagaku*, *24*(2), 137–141. https://doi.org/10.1589/rika.24.137

Anderson, A. F., Dome, D. C., Gautam, S., Awh, M. H., & Rennirt, G. W. (2001). Correlation of anthropometric measurements, strength, anterior cruciate ligament size, and intercondylar notch characteristics to sex differences in anterior cruciate ligament tear rates. *The American Journal of Sports Medicine*, *29*(1), 58–66. https://doi.org/10.1177/03635465010290011501

Anderson, A. F., Lipscomb, A. B., Liudahl, K. J., & Addlestone, R. B. (1987). Analysis of the intercondylar notch by computed tomography. *The American Journal of Sports Medicine*, *15*(6), 547–552. https://doi.org/10.1177/036354658701500605

Arendt, E., & Dick, R. (1995). Knee injury patterns among men and women in collegiate basketball and soccer. *The American Journal of Sports Medicine*, *23*(6), 694–701. https://doi.org/10.1177/036354659502300611

Balogun, J. A. (1987). Assessment of physical fitness of female physical therapy students. *Journal of Orthopaedic & Sports Physical Therapy*, *8*(11), 525–532. https://doi.org/10.2519/jospt.1987.8.11.525

Beekley, M. D., Abe, T., Kondo, M., Midorikawa, T., & Yamauchi, T. (2006). Comparison of normalized maximum aerobic capacity and body composition of sumo wrestlers to athletes in combat and other sports. *Journal of Sports Science & Medicine*, *5*(CSSI), 13–20.

Bennell, K., Wajswelner, H., Lew, P., Schall-Riaucour, A., Leslie, S., Plant, D., & Cirone, J. (1998). Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. *British Journal of Sports Medicine*, *32*(4), 309. https://doi.org/10.1136/bjsm.32.4.309

Bennett, D. R., Blackburn, J. T., Boling, M. C., McGrath, M., Walusz, H., & Padua, D. A. (2008). The relationship between anterior tibial shear force during a jump landing task and quadriceps and hamstring strength. *Clinical Biomechanics*, *23*(9), 1165–1171. https://doi.org/10.1016/j.clinbiomech.2008.05.005

Boden, B. P., Dean, G. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics*, *23*(6), 573–578. https://doi.org/10.3928/0147-7447-20000601-15

Bojicic, K. M., Beaulieu, M. L., Krieger, D. Y. I., Ashton-Miller, J. A., & Wojtys, E. M. (2017). Association between lateral posterior tibial slope, body mass index, and ACL injury risk. *Orthopaedic Journal of Sports Medicine*, *5*(2), 2325967116688664. https://doi.org/10.1177/2325967116688664

Branch, T. P., Browne, J. E., Campbell, J. D., Siebold, R., Freedberg, H. I., Arendt, E. A., Lavoie, F., Neyret, P., & Jacobs, C. A. (2010). Rotational laxity greater in patients with contralateral anterior cruciate ligament injury than healthy volunteers. *Knee Surgery, Sports Traumatology, Arthroscopy*, *18*(10), 1379–1384. https://doi.org/10.1007/s00167-009-1010-y

Brophy, R., Silvers, H. J., Gonzales, T., & Mandelbaum, B. R. (2010). Gender influences: The role of leg dominance in ACL injury among soccer players. *British Journal of Sports Medicine*, *44*(10), 694. https://doi.org/10.1136/bjsm.2008.051243

Camic, C. L., Housh, T. J., Weir, J. P., Zuniga, J. M., Hendrix, C. R., Mielke, M., Johnson, G. O., Housh, D. J., & Schmidt, R. J. (2010). Influences of body-size variables on age-related increases in isokinetic peak torque in young wrestlers. *Journal of Strength and Conditioning Research*, *24*(9), 2358–2365. https://doi.org/10.1519/jsc.0b013e3181aff2a2

Charlton, W. P. H., John, T. A. St., Ciccotti, M. G., Harrison, N., & Schweitzer, M. (2002). Differences in femoral notch anatomy between men and women. *The American Journal of Sports Medicine*, *30*(3), 329–333. https://doi.org/10.1177/03635465020300030501

Chaudhari, A. M. W., Zelman, E. A., Flanigan, D. C., Kaeding, C. C., & Nagaraja, H. N. (2009). Anterior cruciate ligament—injured subjects have smaller anterior cruciate ligaments than matched controls. *The American Journal of Sports Medicine*, *37*(7), 1282–1287. https://doi.org/10.1177/0363546509332256

Colby, S., Francisco, A., Yu, B., Kirkendall, D., Finch, M., & Garrett, W. (2000). Electromyographic and kinematic analysis of cutting maneuvers. Implications for anterior cruciate ligament injury. *The American Journal of Sports Medicine*, *28*(2), 234–240. https://doi.org/10.1177/03635465000280021501

Coombs, R., & Garbutt, G. (2002). Developments in the use of the hamstring/quadriceps ratio for the assessment of muscle balance. *Journal of Sports Science & Medicine*, *1*(3), 56–62.

Del Monte, M. J., Opar, D. A., Timmins, R. G., Ross, J. A., Keogh, J. W., & Lorenzen, C. (2020). Hamstring myoelectrical activity during three different kettlebell swing exercises. *The Journal of Strength & Conditioning Research*, *34*(7), 1953-1958. https://doi.org/10.1519/JSC.0000000000002254

Dibrezzo, R., Gench, B. E., Hinson, M. M., & King, J. (1985). Peak torque values of the knee extensor and flexor muscles of females. *The Journal of Orthopaedic and Sports Physical Therapy*, *7*(2), 65–68. https://doi.org/10.2519/jospt.1985.7.2.65

Evans, K. N., Kilcoyne, K. G., Dickens, J. F., Rue, J.-P., Giuliani, J., Gwinn, D., & Wilckens, J. H. (2012). Predisposing risk factors for non-contact ACL injuries in military subjects. *Knee Surgery, Sports Traumatology, Arthroscopy*, *20*(8), 1554–1559. https://doi.org/10.1007/s00167-011-1755-y

Fleming, B. C., Renström, P. A., Beynnon, B. D., Engstrom, B., Peura, G. D., Badger, G. J., & Johnson, R. J. (2001). The effect of weightbearing and external loading on anterior cruciate ligament strain. *Journal of Biomechanics*, *34*(2), 163–170. https://doi.org/10.1016/s0021-9290(00)00154-8

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Medicine & Science in Sports & Exercise*, *35*(10), 1745–1750. https://doi.org/10.1249/01.mss.0000089346.85744.d9

Goshima, K., Kitaoka, K., Shima, Y., Nakase, J., Takahashi, R., & Tsuchiya, H. (2011). Video analysis of anterior cruciate ligament injuries in sumo wrestling. *British Journal of Sports Medicine*, *45*(4), 351. https://doi.org/10.1136/bjsm.2011.084038.116

Griffin, L. Y., Albohm, M. J., Arendt, E. A., Bahr, R., Beynnon, B. D., DeMaio, M., Dick, R. W., Engebretsen, L., Garrett, W. E., Hannafin, J. A., Hewett, T. E., Huston, L. J., Ireland, M. L., Johnson, R. J., Lephart, S., Mandelbaum, B. R., Mann, B. J., Marks, P. H., Marshall, S. W., … Yu, B. (2006). Understanding and preventing noncontact anterior cruciate ligament injuries. *The American Journal of Sports Medicine*, *34*(9), 1512–1532. https://doi.org/10.1177/0363546506286866

Grygorowicz, M., Michalowska, M., Walczak, T., Grabski, J., Pyda, A., & Piontek, T. (2017). Hamstring/quadriceps ratio in ACL injury prediction in elite football players. *British Journal of Sports Medicine*, *51*(4), 326. https://doi.org/10.1136/bjsports-2016-097372.108

Grygorowicz, M., Michałowska, M., Walczak, T., Owen, A., Grabski, J. K., Pyda, A., Piontek, T., & Kotwicki, T. (2017). Discussion about different cut-off values of conventional hamstring-to-quadriceps ratio used in hamstring injury prediction among professional male football players. *PLoS ONE*, *12*(12), e0188974. https://doi.org/10.1371/journal.pone.0188974

Haddara, R., Harandi, V. J., & Lee, P. V. S. (2020). Anterior cruciate ligament agonist and antagonist muscle force differences between males and females during perturbed walking. *Journal of Biomechanics*, *110*, 109971. https://doi.org/10.1016/j.jbiomech.2020.109971

Hame, S. L., Oakes, D. A., & Markolf, K. L. (2002). Injury to the anterior cruciate ligament during alpine skiing: A biomechanical analysis of tibial torque and knee flexion angle. *The American Journal of Sports Medicine*, *30*(4), 537–540. https://doi.org/10.1177/03635465020300041301

Heiser, T. M., Weber, J., Sullivan, G., Clare, P., & Jacobs, R. R. (1984). Prophylaxis and management of hamstring muscle injuries in intercollegiate football players. *The American Journal of Sports Medicine*, *12*(5), 368–370. https://doi.org/10.1177/036354658401200506

Heitz, N. A., Eisenman, P. A., Beck, C. L., & Walker, J. A. (1999). Hormonal changes throughout the menstrual cycle and increased anterior cruciate ligament laxity in females. *Journal of Athletic Training*, *34*(2), 144–149.

Hohmann, E., Tetsworth, K., & Glatt, V. (2006). The hamstring/quadriceps ratio is an indicator of function in ACL-deficient, but not in ACL-reconstructed knees. *Archives of Orthopaedic and Trauma Surgery*, *139*(1), 91–98. https://doi.org/10.1007/s00402-018-3000-3

Housh, T. J., Johnson, G. O., Hughes, R. A., Housh, D. J., Hughes, R. J., Fry, A. S., Kenney, K. B., & Cisar, C. J. (1989). Isokinetic strength and body composition of high school wrestlers across age. *Medicine & Science in Sports & Exercise*, *21*(1), 105. https://doi.org/10.1249/00005768-198902000-00019

Hughes, G., & Watkins, J. (2006). A risk-factor model for anterior cruciate ligament injury. *Sports Medicine*, *36*(5), 411–428. https://doi.org/10.2165/00007256-200636050-00004

Huston, L. J., & Wojtys, E. M. (1996). Neuromuscular performance characteristics in elite female athletes. *The American Journal of Sports Medicine*, *24*(4), 427–436. https://doi.org/10.1177/036354659602400405

Jensen, R. L., & Ebben, W. P. (2000). Hamstring electromyographic response of the back squat at different knee angles during concentric and eccentric phases. In *ISBS-Conference Proceedings Archive*.

Jónasson, G., Helgason, A., Ingvarsson, Þ., Kristjánsson, A. M., & Briem, K. (2016). The effect of tibial rotation on the contribution of medial and lateral hamstrings during isometric knee flexion. *Sports Health, 8*(2), 161–166. https://doi.org/10.1177/1941738115625039

Keays, S. L., Keays, R., & Newcombe, P. A. (2016). Femoral intercondylar notch width size: A comparison between siblings with and without anterior cruciate ligament injuries. *Knee Surgery, Sports Traumatology, Arthroscopy*, *24*(3), 672–679. https://doi.org/10.1007/s00167-014-3491-6

Kim, S. Y., Spritzer, C. E., Utturkar, G. M., Toth, A. P., Garrett, W. E., & DeFrate, L. E. (2015). Knee kinematics during noncontact anterior cruciate ligament injury as determined from bone bruise location. *The American Journal of Sports Medicine*, *43*(10), 2515–2521. https://doi.org/10.1177/0363546515594446

Kızılgöz, V., Sivrioğlu, A. K., Ulusoy, G. R., Aydın, H., Karayol, S. S., & Menderes, U. (2018). Analysis of the risk factors for anterior cruciate ligament injury: An investigation of structural tendencies. *Clinical Imaging*, *50*, 20–30. https://doi.org/10.1016/j.clinimag.2017.12.004

Knapik, J. J., Bauman, C. L., Jones, B. H., Harris, J. McA., & Vaughan, L. (1991). Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes. *The American Journal of Sports Medicine*, *19*(1), 76–81. https://doi.org/10.1177/036354659101900113

Krosshaug, T., Nakamae, A., Boden, B. P., Engebretsen, L., Smith, G., Slauterbeck, J. R., Hewett, T. E., & Bahr, R. (2007). Mechanisms of anterior cruciate ligament injury in basketball. *The American Journal of Sports Medicine*, *35*(3), 359–367. https://doi.org/10.1177/0363546506293899

Li, R. C., Maffulli, N., Hsu, Y. C., & Chan, K. M. (1996). Isokinetic strength of the quadriceps and hamstrings and functional ability of anterior cruciate deficient knees in recreational athletes. *British Journal of Sports Medicine*, *30*(2), 161. https://doi.org/10.1136/bjsm.30.2.161

Lightfoot, A. J., McKinley, T., Doyle, M., & Amendola, A. (2005). ACL tears in collegiate wrestlers: Report of six cases in one season. *The Iowa Orthopaedic Journal*, *25*, 145–148.

Lombardo, S., Sethi, P. M., & Starkey, C. (2005). Intercondylar notch stenosis is not a risk factor for anterior cruciate ligament tears in professional male basketball players: An 11-year prospective study. *The American Journal of Sports Medicine*, *33*(1), 29–34. https://doi.org/10.1177/0363546504266482

Malinzak, R. A., Colby, S. M., Kirkendall, D. T., Yu, B., & Garrett, W. E. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clinical Biomechanics*, *16*(5), 438–445. https://doi.org/10.1016/s0268-0033(01)00019-5

McLean, S. G., Oh, Y. K., Palmer, M. L., Lucey, S. M., Lucarelli, D. G., Ashton-Miller, J. A., & Wojtys, E. M. (2011). The relationship between anterior tibial acceleration, tibial slope, and ACL strain during a simulated jump landing task. *The Journal of Bone & Joint Surgery*, *93*(14), 1310–1317. https://doi.org/10.2106/jbjs.j.00259

Meyer, E. G., & Haut, R. C. (2008). Anterior cruciate ligament injury induced by internal tibial torsion or tibiofemoral compression. *Journal of Biomechanics*, *41*(16), 3377–3383. https://doi.org/10.1016/j.jbiomech.2008.09.023

Mohamed, E., Useh, U., & Mtshali, B. (2012). Q-angle, pelvic width, and intercondylar notch width as predictors of knee injuries in women soccer players in South Africa. *African Health Sciences*, *12*(2), 174–180. https://doi.org/10.4314/ahs.v12i2.15

Mokhtarzadeh, H., Ewing, K., Janssen, I., Yeow, C.-H., Brown, N., & Lee, P. V. S. (2017). The effect of leg dominance and landing height on ACL loading among female athletes. *Journal of Biomechanics*, *60*, 181–187. https://doi.org/10.1016/j.jbiomech.2017.06.033

More, R. C., Karras, B. T., Neiman, R., Fritschy, D., Woo, S. L.-Y., & Daniel, D. M. (1993). Hamstrings—an anterior cruciate ligament protagonist. *The American Journal of Sports Medicine*, *21*(2), 231–237. https://doi.org/10.1177/036354659302100212

Moul, J. L. (1998). Differences in selected predictors of anterior cruciate ligament tears between male and female NCAA division I collegiate basketball players. *Journal of Athletic Training*, *33*(2), 118–121.

Muneta, T., Takakuda, K., & Yamamoto, H. (1997). Intercondylar notch width and its relation to the configuration and cross-sectional area of the anterior cruciate ligament: A cadaveric knee study. *The American Journal of Sports Medicine*, *25*(1), 69–72. https://doi.org/10.1177/036354659702500113

Myer, G. D., Ford, K. R., Foss, K. D. B., Liu, C., Nick, T. G., & Hewett, T. E. (2009). The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clinical Journal of Sport Medicine*, *19*(1), 3–8. https://doi.org/10.1097/jsm.0b013e318190bddb

Myer, G. D., Ford, K. R., Paterno, M. V., Nick, T. G., & Hewett, T. E. (2008). The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. *The American Journal of Sports Medicine*, *36*(6), 1073–1080. https://doi.org/10.1177/0363546507313572

Negrete, R. J., Schick, E. A., & Cooper, J. P. (2007). Lower-limb dominance as a possible etiologic factor in noncontact anterior cruciate ligament tears. *The Journal of Strength & Conditioning Research*, *21*(1), 270. https://doi.org/10.1519/00124278-200702000-00048

Nunley, R. M., Wright, D., Renner, J. B., Yu, B., & Jr, W. E. G. (2003). Gender comparison of patellar tendon tibial shaft angle with weight bearing. *Research in Sports Medicine: An International Journal*, *11*(3), 173–185. https://doi.org/10.1080/15438620390231193

Oh, Y. K., Lipps, D. B., Ashton-Miller, J. A., & Wojtys, E. M. (2012). What strains the anterior cruciate ligament during a pivot landing? *The American Journal of Sports Medicine*, *40*(3), 574–583. https://doi.org/10.1177/0363546511432544

Orchard, J., Marsden, J., Lord, S., & Garlick, D. (1997). Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *The American Journal of Sports Medicine*, *25*(1), 81–85. https://doi.org/10.1177/036354659702500116

Otero, J. E., Graves, C. M., & Bollier, M. J. (2017). Injuries in collegiate wrestlers at an elite Division I NCAA wrestling program: An epidemiological study. *The Iowa Orthopaedic Journal*, *37*, 65–70.

Polat, S. Ç., Bulgay, C., Yarım, İ., Cicioğlu, H. İ., & Çetin, E. (2018). Analysis of the relationship between elite wrestlers' leg strength and balance performance, and injury history. *Sports*, *6*(2), 35. https://doi.org/10.3390/sports6020035

Quatman, C. E., Kiapour, A. M., Demetropoulos, C. K., Kiapour, A., Wordeman, S. C., Levine, J. W., Goel, V. K., & Hewett, T. E. (2013). Preferential loading of the ACL compared with the MCL during landing: A novel in sim approach yields the multiplanar mechanism of dynamic valgus during ACL injuries. *The American Journal of Sports Medicine*, *42*(1), 177–186. https://doi.org/10.1177/0363546513506558

Renström, P., Arms, S. W., Stanwyck, T. S., Johnson, R. J., & Pope, M. H. (1986). Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *The American Journal of Sports Medicine*, *14*(1), 83–87. https://doi.org/10.1177/036354658601400114

Roemmich, J. N., & Sinning, W. E. (1997). Weight loss and wrestling training: effects on nutrition, growth, maturation, body composition, and strength. *Journal of Applied Physiology*, *82*(6), 1751–1759. https://doi.org/10.1152/jappl.1997.82.6.1751

Schickendantz, M. S., & Weiker, G. G. (1993). The predictive value of radiographs in the evaluation of unilateral and bilateral anterior cruciate ligament injuries. *The American Journal of Sports Medicine*, *21*(1), 110-113. https://doi.org/10.1177/036354659302100118

Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2009). The effect of isolated valgus moments on ACL strain during single-leg landing: A simulation study. *Journal of Biomechanics*, *42*(3), 280–285. https://doi.org/10.1016/j.jbiomech.2008.10.031

Shultz, S. J., Schmitz, R. J., Cameron, K. L., Ford, K. R., Grooms, D. R., Lepley, L. K., Myer, G. D., & Pietrosimone, B. (2019). Anterior cruciate ligament research retreat VIII summary statement: an update on injury risk identification and prevention across the anterior cruciate ligament injury continuum, March 14–16, 2019, Greensboro, NC. *Journal of Athletic Training*, *54*(9), 970–984. https://doi.org/10.4085/1062-6050-54.084

Shultz, S. J., Schmitz, R. J., Kong, Y., Dudley, W. N., Beynnon, B. D., Nguyen, A. D., Kim, H., & Montgomery, M. M. (2012). Cyclic variations in multiplanar knee laxity influence landing biomechanics. *Medical Science in Sports and Exercise, 44*(5), 900-909. https://doi.org/10.1249/MSS.0b013e31823bfb25

Simon, R. A., Everhart, J. S., Nagaraja, H. N., & Chaudhari, A. M. (2010). A case-control study of anterior cruciate ligament volume, tibial plateau slopes and intercondylar notch dimensions in ACL-injured knees. *Journal of Biomechanics*, *43*(9), 1702–1707. https://doi.org/10.1016/j.jbiomech.2010.02.033

Tatlıcıoğlu, E., Atalağ, O., Kırmızıgil, B., Kurt, C., & Acar, M. F. (2019). Side-to-side asymmetry in lower limb strength and hamstring-quadriceps strength ratio among collegiate American football players. *Journal of Physical Therapy Science*, *31*(11), 884–888. https://doi.org/10.1589/jpts.31.884

Uhorchak, J. M., Scoville, C. R., Williams, G. N., Arciero, R. A., Pierre, P. S., & Taylor, D. C. (2003). Risk factors associated with noncontact injury of the anterior cruciate ligament: A prospective four-year evaluation of 859 West Point cadets. *The American Journal of Sports Medicine*, *31*(6), 831–842.

Waldén, M., Krosshaug, T., Bjørneboe, J., Andersen, T. E., Faul, O., & Hägglund, M. (2015). Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *British Journal of Sports Medicine*, *49*(22), 1452–1460. https://doi.org/10.1136/bjsports-2014-094573

Weesner, C. L., Albohm, M. J., & Ritter, M. A. (2016). A comparison of anterior and posterior cruciate ligament laxity between female and male basketball players. *The Physician and Sportsmedicine*, *14*(5), 149–154. https://doi.org/10.1080/00913847.1986.11709076

Weinhandl, J. T., Earl-Boehm, J. E., Ebersole, K. T., Huddleston, W. E., Armstrong, B. S. R., & O'Connor, K. M. (2014). Reduced hamstring strength increases anterior cruciate ligament loading during anticipated sidestep cutting. *Clinical Biomechanics*, *29*(7), 752–759. https://doi.org/10.1016/j.clinbiomech.2014.05.013

Wieschhoff, G. G., Mandell, J. C., Czuczman, G. J., Nikac, V., Shah, N., & Smith, S. E. (2017). Acute non-contact anterior cruciate ligament tears are associated with relatively increased vastus medialis to semimembranosus cross-sectional area ratio: A case-control retrospective MR study. *Skeletal Radiology*, *46*(11), 1469–1475. https://doi.org/10.1007/s00256-017-2709-3

Withrow, T. J., Huston, L. J., Wojtys, E. M., & Ashton-Miller, J. A. (2006). The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing. *The American Journal of Sports Medicine*, *34*(2), 269–274. https://doi.org/10.1177/0363546505280906

Wojtys, E. M., Huston, L. J., Boynton, M. D., Spindler, K. P., & Lindenfeld, T. N. (2002). The effect of the menstrual cycle on anterior cruciate ligament injuries in women as determined by hormone levels. *The American Journal of Sports Medicine*, *30*(2), 182–188. https://doi.org/10.1177/03635465020300020601

Yard, E. E., & Comstock, R. D. (2007). A comparison of pediatric freestyle and Greco-Roman wrestling injuries sustained during a 2006 US national tournament: Comparison of pediatric freestyle and Greco-Roman wrestling injuries. *Scandinavian Journal of Medicine & Science in Sports*, *18*(4), 491–497. https://doi.org/10.1111/j.1600-0838.2007.00716.x

Yeung, S. S., Suen, A. M. Y., & Yeung, E. W. (2009). A prospective cohort study of hamstring injuries in competitive sprinters: Preseason muscle imbalance as a possible risk factor. *British Journal of Sports Medicine*, *43*(8), 589. https://doi.org/10.1136/bjsm.2008.056283

Appendix A

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