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The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes

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Abstract

Objective: The purpose of the current investigation was to determine the association of quadriceps and hamstrings strength to ACL injury risk in female athletes. The primary hypothesis was that there would be decreased knee flexor and increased knee extensor strength in female athletes who went on to ACL injured status (FACL) compared to uninjured female (FC) and male (MC) control subjects.

Study Design: Matched case control

Setting: Institutional Biomechanics Laboratory

Participants: Prospectively measured FACL (n=22) females who subsequently suffered confirmed non-contact ACL ruptures (16 during soccer and 6 during basketball play) were matched to (1:4 ratio) female controls (FC; n=88) using limb (dominant or non-dominant), pubertal status, sport and nearest height and mass. In addition, males (MC) were matched (1:1 ratio) to FACL to serve as a secondary comparative control.

Assessment of Risk Factors: Isokinetic (concentric) knee extension/flexion strength (300°/s).

Results: FACL subjects had decreased hamstrings strength compared to MC [15% (95% C.I. 1%, 27%); P=0.04]. FC were not different than MC in hamstrings strength. Conversely, FACL subjects did not differ compared to the MC in quadriceps strength and the FC demonstrated decreased quadriceps strength relative to MC [10% (95% C.I. 3%,18%); P=0.01].

Conclusions: The results of this investigation indicate that female athletes who suffered ACL injury subsequent to strength testing had a combination of decreased hamstrings, but not

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quadriceps, strength compared to males. In direct contrast, female athletes who did not go on to ACL injury had decreased quadriceps strength and similar hamstrings strength compared to matched male athletes.

Keywords

Knee flexor to extensor ratio; Isokinetic outcome measure; Anterior Cruciate Ligament injury prediction; Knee torques; Knee co-contraction

INTRODUCTION

Females who participate in high-risk sports suffer ACL injury at a 4 to 6-fold greater rate than males.[1] Lack of active neuromuscular control, as evidenced by increased knee abduction motion and torque[2] and passive stability of the joint, as evidenced by increased joint laxity[3] may destabilize the knee and are predictive of increased ACL injury risk in female athletes. ACL injury likely occurs under conditions of high dynamic loading of the knee joint, when active muscular restraints do not adequately compensate for and adequately dampen joint loads.[4] Decreased neuromuscular control of the joint may place stress on the passive ligament structures that exceed the failure strength of the ligament.[5, 6] Neuromuscular control of high load movements is required to maintain dynamic knee stability during landing and pivoting.[5, 7, 8] Hamstrings and quadriceps co-contraction may provide dynamic joint stabilization and potentially protect the knee during sports related tasks.[5, 8–10] Males demonstrate increased relative strength[11–13] and relative recruitment[13, 14] of the hamstrings compared to quadriceps during dynamic knee loading tasks. Ford and colleagues reported that females utilize increased quadriceps activation without matched increases in hamstrings activation as they perform drop landings with incrementally increased drop height intensity.[15] Decreased hamstrings relative to quadriceps strength and recruitment is implicated as a potential mechanism for increased lower extremity injuries.[10, 15–18] Deficits in relative hamstrings strength and recruitment may also contribute to increased ACL injury risk in female athletes.

The purpose of the current investigation was to determine the association of quadriceps and hamstrings isokinetic strength to ACL injury risk in female athletes. The primary hypothesis was that decreased knee flexor and increased knee extensor strength would be observed in female athletes who would subsequently suffer ACL injury (FACL) compared to uninjured female (FC) and male (MC) control subjects.

METHODS

Subjects

A matched case control study design (n=132 total, 22 FACL, 110 controls) was used to sample female and male high school and collegiate soccer and basketball players who were prospectively screened (2002–2007; n =1692 potential samples) for hamstrings and quadriceps strength measures prior to their recorded ACL injury. FACL (n=22) females subsequently suffered arthroscopically-confirmed non-contact ACL ruptures (16 during soccer and 6 during basketball play). FACL injuries occurred in a range of one month to two years from date of testing. Each FACL case was matched to 4 female controls (FC; n=88) using limb (dominant or non-dominant), pubertal status, sport and nearest height and mass. In addition, males (MC) were also matched using limb, pubertal status and nearest height and mass matched (1:1 ratio) to FACL to serve as a secondary comparative control.

Informed written consent was obtained from all subjects and their parents and approved by the Institutional Review Board. After the informed consent was obtained, height and mass were measured and recorded. Isokinetic strength and vertical jump height measures were recorded during the laboratory evaluation during each athlete's visit for their prospective screening. Included within the consent form was a detailed medical history and previous sport participation questionnaire.

Maturational Status

The modified Pubertal Maturational Observational Scale (PMOS) has been shown to provide reliable assessment of pubertal status and one rater was used to classify each subject in the current study into one of three pubertal categories (pre-pubertal, pubertal and post-pubertal).[19–23]

Vertical Jump Height Testing

Figure 1 presents vertical jump measurement on the MX1 vertical jump trainer (MXP Sports, Reading, Pennsylvania). Prior authors have demonstrated that counter movement vertical jump testing has a test-retest reliability of R=0.993.[24]

Dynamic Strength

Isokinetic knee extension/flexion (concentric/concentric muscle action) strength was collected with each subject seated on the dynamometer and the trunk perpendicular to floor, the hip flexed to 90° and the knee flexed to 90°. Prior to each data collection set, a warm-up set, which consisted of 5 sub-maximal knee flexion/extensions for each leg at 300°/sec, was performed. The test session consisted of 10 knee isokinetic extension/flexion (100° to 0° range of motion) repetitions for each leg at 300°/second (Figure 2). Peak flexion and extension torques were recorded (ft·lbs). Isokinetic concentric strength measures of hamstrings and quadriceps strength demonstrate excellent reliability.[25]

Statistical method

Descriptive statistics were calculated to characterize the study population. Due to the skewness of the data, medians and interquartile ranges (the difference between 25th and 75th percentiles) were reported. Natural log transformations were taken on all response measures and used for subsequent modeling. Logs were found to be appropriate based on the Box-Cox transformation computed using PROC TRANSREG in SAS (SAS Institute, Cary, NC). To account for the matching strategy, a linear mixed model using PROC MIXED in SAS was fitted on each response to compare case-control differences. The matching variable was treated as a random effect. To take into account the difference in individual physical capabilities, vertical jump height was added to each model as a control variable to explain part of the variability in response. To relate to the original scale of the data, a back-transform (antilog) was used on the mean log difference to compute the geometric mean of a ratio defined as the ratio of one group compared to a reference group.

RESULTS

The matched case control study design yielded 110 female and 22 male middle school, high school and collegiate soccer and basketball players who were all prospectively screened for strength measures prior to the recorded ACL injury for the FACL subjects. The FACL sample was similar in height (FACL: 165.6 ± 6.5 vs. FC: 164.9 ± 5.5 vs. MC: 167.2 ± 5.7 cm, P=0.25) and mass (FACL: 58.8 ± 7.3 vs. FC: 58.2 ± 7.1 vs. MC: 60.2 ± 7.7 kg, P=0.51) to their matched male and female controls. Nineteen of the FACL were categorized as post-pubertal while 3 were categorized as pubertal at time of assessment.

Figure 3 presents the median values for hamstrings to quadriceps strength ratio (H/Q), while the interquartile ranges of the recorded hamstrings peak torque, quadriceps peak torque and vertical jump height for each group are presented in Table 1. These were unadjusted measurements and did not account for matching. The comparisons in each response between the matched groups were summarized in Figure 4. Because the geometric means was used for the log transformed data, the results can be interpreted in terms of percent change.

Female athletes who subsequently suffered ACL injury had decreased hamstrings strength, but not decreased similar quadriceps strength, compared to matched control males. Conversely, female athletes who did not go on to ACL injury had decreased quadriceps strength, but not decreased hamstrings strength compared to matched male athletes. Although the median measurements in quadriceps and hamstrings strength were similar in FACL and FC groups, Figure 3 shows that FACL subjects had 15% decreased hamstrings strength compared to MC [95% confidence interval, CI 1%, 27%; P=0.04], while FC were not different than MC in hamstrings strength (P=0.08) after adjusting for vertical jump height and taking into account the random effects arising from the matching. Conversely, the FC demonstrated a 10% decreased in quadriceps strength relative to MC (95% CI 3% to 18%; P=0.01). FACL subjects did not differ compared to the MC in quadriceps strength (P=0.14).

DISCUSSION

Prior critiques of similar epidemiological designs to determine risk factors for ACL injury have expressed concern about the confounding effects of sport, height and mass.[2, 26] This investigation incorporated an approach to control for potential confounding variance between individual sport, maturational status and individual anthropometrics, through the utilization of matched case subjects with subjects of the same sport, pubertal status and nearest height and mass, to serve as uninjured control subjects. In addition, this study utilized a novel approach to compare matched male athletes to control for potential confounding variance in whole body power and maturational status between investigational and control subjects. Cumulatively, the high number of control measures in this investigation were employed to provide a more robust interpretation of isolated strength mechanisms and their relationship to ACL injury in female athletes. The results of the current investigation indicate that when controlling for whole body power, FACL demonstrate similar relative quadriceps strength but decreased hamstrings strength compared to uninjured male athletes. This finding indicates that decreased relative hamstrings strength and recruitment may be a potential contributing mechanism to ACL injury in high risk female athletes.

A previous study showed that male and female relative hamstrings to quadriceps strength profiles diverge significantly during and following puberty.[12, 21] Isokinetic dynamometer measurements show that male athletes demonstrate significantly greater hamstrings peak torques with increasing maturity, while peak hamstrings torque remain stable with increasing maturational stage in female athletes.[21] In addition, sex differences in isokinetic H/Q ratios are not detected in post-pubertal athletes at slower angular velocities. However, at high knee flexion/extension angular velocities, approaching those that occur during sports activities, significant gender differences become evident in H/Q ratio.[11] Females, unlike males, do not increase hamstrings to quadriceps torque ratios at velocities that approach those of functional activities.[11] Thus, it appears that decreased hamstrings strength and H/Q ratios of female athletes relative to males may be related to the development of neuromuscular imbalances associated with the onset of maturation.[12, 21, 27] These neuromuscular imbalances may increase ACL injury risk in pubertal and post pubertal female athletes as was indicated by the current results with all FACL subject either pubertal or post-pubertal at the time of injury.[2, 21, 28]

Decreased hamstrings strength relative to the quadriceps is implicated as a potential mechanism for increased lower extremity injuries.[8, 15–17] and potentially ACL injury risk in female athletes.[18] Joint stability through hamstrings and quadriceps co-contraction may be necessary when the joint experiences high quadriceps activation or when the passive structures are compromised.[29, 30] Withrow and colleagues reported that increased hamstrings force during the flexion phase of simulated jump landings greatly decreased relative strain on the ACL.[10] Another proposed theory related to neuromuscular imbalances and increased ACL injury risk in females is the relatively low knee flexor to extensor recruitment which is reflective of a closed chain dynamic H/Q.[13, 14] For example, hamstrings activation can decrease the load on the passive restraints of the knee,[31] increase the knee joint compression force and stabilize the knee from external varus/valgus load.[32] Hewett et al. reported that males demonstrated knee flexor moments, measured using inverse dynamics, that were three-fold higher than females when decelerating from a landing.[13] This group of females also demonstrated decreased isokinetically measured H/Q ratio and increased knee abduction (valgus) moments compared to male subjects. The increased knee valgus moment significantly correlated to the peak impact forces during the maneuver and is purported to increase ACL injury risk in female athletes.[2, 13] Ford and colleagues reported that females showed an absence of matched increased hamstrings muscle activation relative to quadriceps and overall low amplitude during the landing phase of a jump.[15] This tendency of female athletes to preferentially activate the quadriceps relative to the hamstrings during high demand activities may limit their ability to maintain dynamic knee control during high risk maneuvers.

This quadriceps dominance, or decreased recruitment of hamstrings relative to the quadriceps, has also been observed in elite female collegiate athletes.[33] Female athletes reacted to a forward translation of the tibia primarily with a muscular activation of the quadriceps muscles, while male athletes relied on their hamstrings muscles to counteract the anterior tibial displacement.[34] Malinzak and colleagues examined males and females during more sport specific tasks of running, cross-cutting and side-cutting tasks. They found that females utilized less knee flexion, increased quadriceps activation and decreased hamstrings activation compared to males when performing the three athletic tasks.[35] In addition, Sigward and Powers,[36] examined a side-step cutting maneuver and found that skilled female soccer players had less co-contraction than novice players. These findings indicate that a movement pattern may be "learned," which may elevate possible injury risk in skilled players. Recently, Lawrence and colleagues reported that females in the decreased hip and hamstrings strength group demonstrated increased relative knee extensor activity, ground reaction force and coronal plane knee load when landing on a single leg.[37] Cumulatively, this evidence indicates that decreased relative hamstrings strength may underlie high risk biomechanics in female athletes.[2, 13, 30, 37]

The tendency to land with a straighter knee during high intensity tasks could be exacerbated by early quadriceps, or delayed hamstrings activation, during weight bearing stance.[38] Chappell et al. concluded that the increased anterior shear force demonstrated by the female athletes was potentially due to the combination of increased quadriceps force, decreased hamstrings force and decreased knee flexion.[39] A sagittal plane position of the knee near full extension when landing or cutting is commonly observed in video analysis of ACL injuries in female athletes.[40, 41] In addition, a prospective study indicated that female athletes that subsequently sustained ACL injuries demonstrated significantly less (10.5 degrees) knee flexion when performing a drop vertical jump than those that did not sustain injury.[2] At low knee flexion angles (0 to 30 degrees of knee flexion), quadriceps contractions pull the tibia forward and increase stress on the ACL, especially without balanced knee flexor (hamstrings and gastrocnemius) co-contraction to decrease strain on the ligament.[29, 39, 42] Performing tasks with relatively low knee flexion angles (0 to 30 degrees of knee flexion), in conjunction with relatively large quadriceps contractions, may elicit anterior tibial shear forces that are large enough to rupture the ACL.[39, 43] Increased hamstrings strength and recruitment may decrease ACL injury risk via thru a mechanism of increased relative hamstrings co-contraction that may lead to increased knee flexion and reduced knee abduction and anterior tibial shear during dynamic tasks.[2, 13, 29, 40, 41, 44–47] The FACL subjects in the current study with decreased relative hamstrings strength may have also demonstrated decreased hamstrings recruitment during dynamic tasks, which may have contributed to their injury mechanism; however, muscle activation patterns were not examined in the current study and these neuromuscular parameters cannot be directly determined.

Comprehensive neuromuscular training that combines resistance training with either plyometric training or dynamic balance training can increase knee flexion and decrease dangerous coronal plane knee loads during dynamic tasks, with concomitant increases in relative hamstrings strength in female athletes.[13, 46–48] However, isolated resistance training protocols appear to reduce relative hamstrings to quadriceps ratio and are not effective to alter potential high risk sagittal or coronal plane biomechanics in female athletes.[49, 50] The increased ability to decelerate from a landing and to control dynamic knee valgus may be related to the decreased imbalance in the hamstrings to quadriceps strength and recruitment that was observed in the females prior to training.[51] The increased balance in strength and recruitment of the hamstrings and gastrocnemius musculature relative to quadriceps, may be a mechanism that protects the knee ligaments in male athletes and trained female athletes.[2, 13, 44] Adequate co-contraction of the knee flexors may help balance active contraction of the quadriceps that can compress the joint and assist in the control of high knee abduction torques or valgus collapse. Appropriate neuromuscular control may prevent the critical loading necessary to rupture the ACL during maneuvers that place the athlete at risk for an injury. Female athletes, with decreased ability to adequately balance muscular recruitment through positions of high joint loading, may increase their risk of subsequent ligament failure.[2, 13, 29, 40, 41, 44–47] Therefore, dynamic knee stability during multi-planar movements at the knee, may be contingent upon hamstrings strength and co-activation to resist anterior tibial translation and knee abduction resulting from excessive quadriceps contraction.[13, 45, 52] Based on the results of the current report, increased relative strength and recruitment of the hamstrings musculature achieved through neuromuscular training may be a potential mechanism for successful reduction of ACL injury in female athletes whom lack dynamic knee stability.[2, 13, 44, 46, 47]

STUDY LIMITATIONS

ACL injury in female athletes likely has a multi-factorial etiology, with several potential elements which determine injury mechanism. In specific, increased knee abduction motion and torque[2] and increased knee joint laxity[3] predict increased ACL injury risk in female athletes. This prior epidemiologic data demonstrate that biomechanical factors, may contribute in isolation or combination with other factors, such as anatomical, hormonal and potentially psychological parameters, to increase relative ACL injury rates in female athletes. While this investigation made several efforts to provide the most appropriate control available to sample, it is plausible that contributing and confounding variables were not controlled for in the current study design.

In addition, the muscular strength contributions that occur during ACL injury occur at a high rate of knee joint loading in closed chain situations, with the quadriceps most likely acting with eccentric muscle action with the hip angles more extended that the current test protocol.[53] While the current protocol did measure the strength at relatively high speeds (300°/sec) the difference in muscle action (concentric vs. eccentric) of the quadriceps during open chain measurements may limit the applicability of our findings to conditions that occur during actual ACL injury and limited our potential to determine significant group differences in H/Q measures.

However, the significant effects of group differences in relative FACL hamstrings strength were observed in this study compared to carefully matched males. These differences were not evident in the uninjured control females compared to the males. The observed differences were of a magnitude outside of the protocol’s measurement error and should be considered a potential contributing mechanism to increased ACL injury risk in female athletes.

Conclusions

The results of this investigation indicate that female athletes who went on to suffer ACL injury had a combination of decreased hamstrings strength, but not decreased similar quadriceps strength, compared to males. In direct contrast, female athletes who did not go on to ACL injury had decreased quadriceps strength, but not decreased hamstrings strength compared to matched male athletes. Female athletes who demonstrate the combination decreased relative hamstrings and high relative quadriceps strength may be at increased risk for ACL injury. Preseason screening programs that monitor hamstrings and quadriceps strength, especially relative to comparable male values, may be warranted to identify female athletes with potential deficits. Targeted neuromuscular interventions that increase relative hamstrings muscle strength and recruitment may decrease injury risk and potentially increase performance in this population.

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Figure 1.
A. Example of reach testing. B. Example of maximum effort countermovement vertical jump testing.

Figure 2.
Example of the isokinetic knee flexion/extension testing.

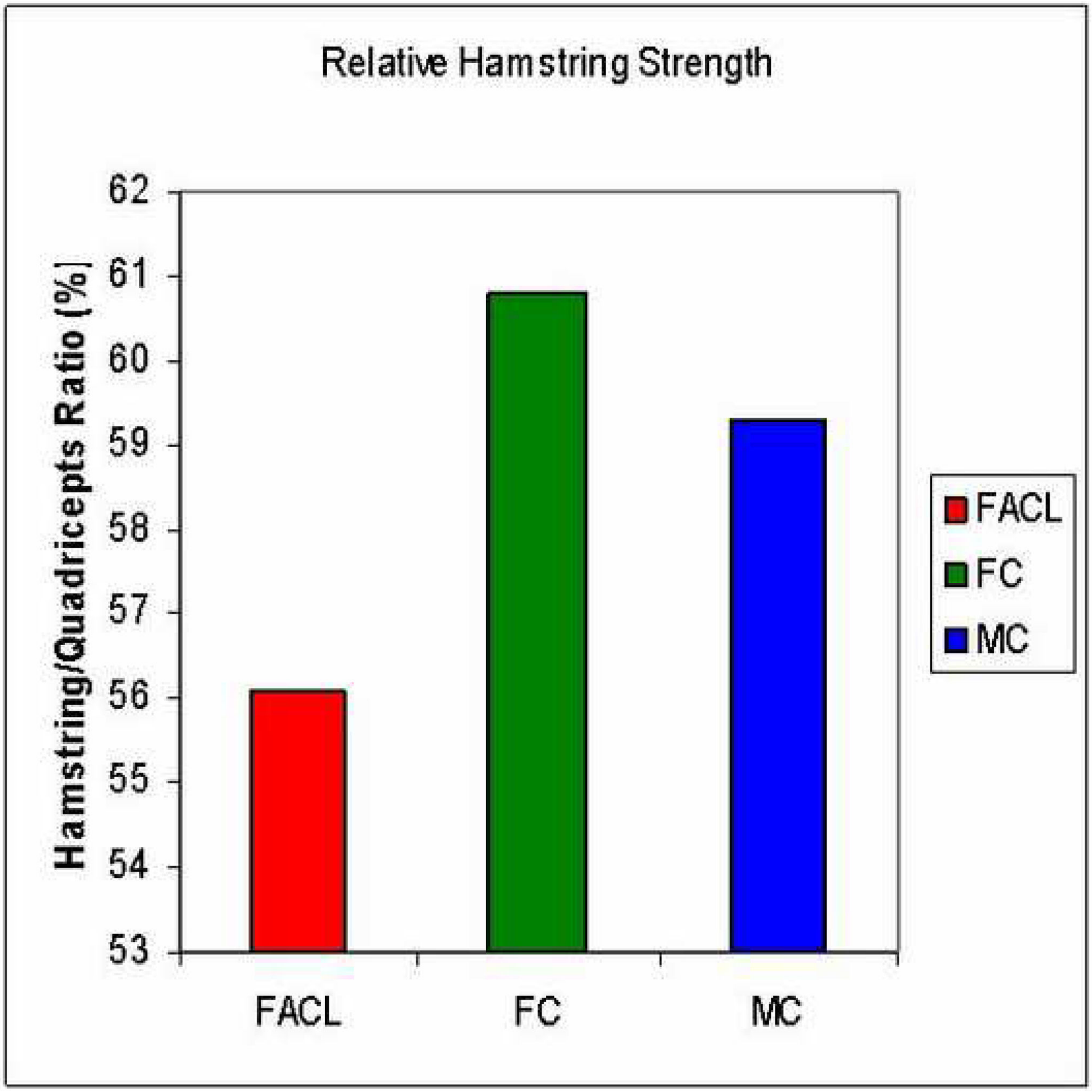

Figure 3.
Median hamstrings to quadriceps ratio for each of the matched comparison groups. **(Female ACL injured-FACL; Female Control-FC; Male Control-MC)**

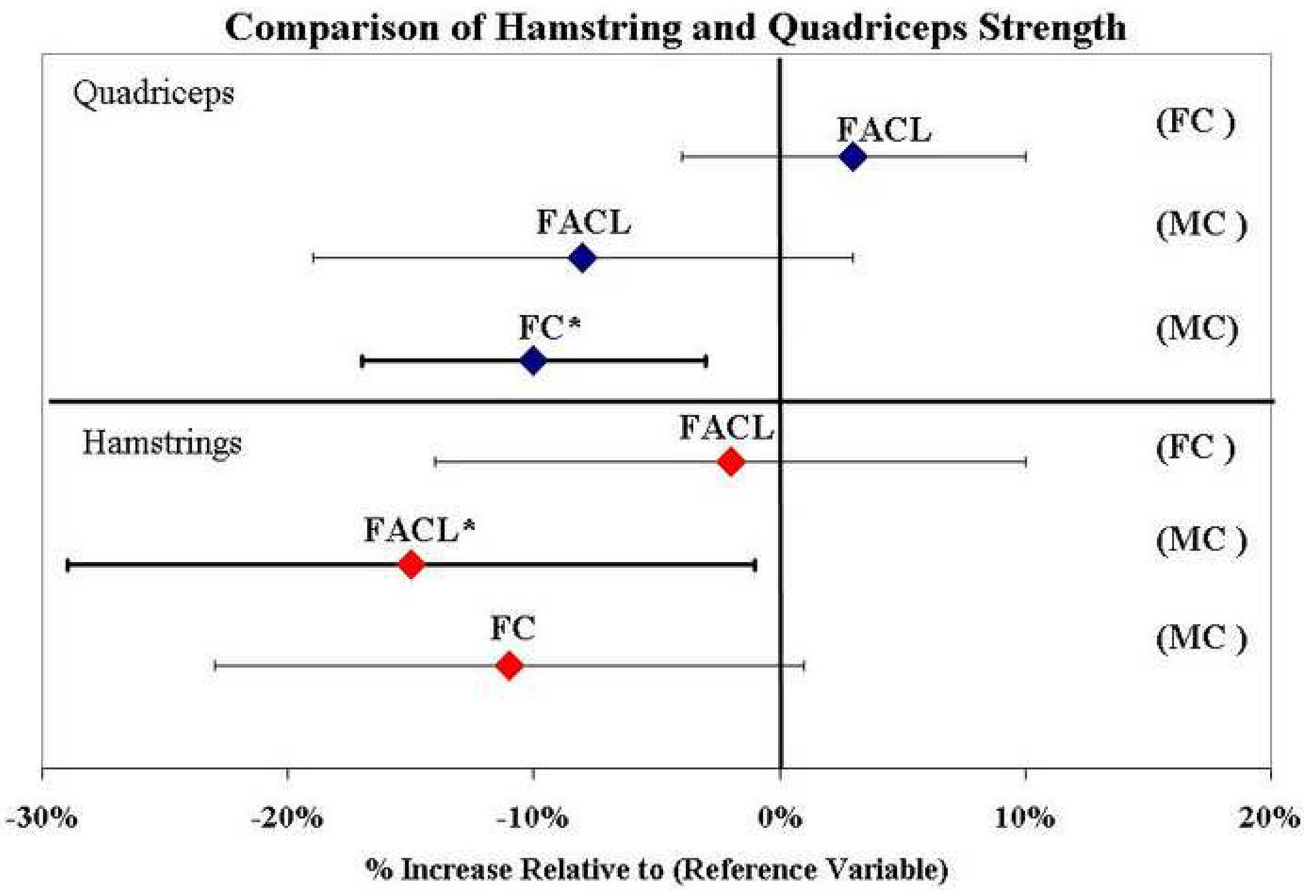

Figure 4.

Ratio and 95% CI for all responses computed using a back-transform on the mean log difference. **(Female ACL injured-FACL; Female Control-FC; Male Control-MC)** * $p<0.05$

Table 1.

Interquartile ranges (25^{th}, 50^{th}, 75^{th}) of response variables and covariate.

Response	FACL (n=22)	FC (n=88)	MC (n=22)
Quadriceps (ft·lbs)	(51.9, 56.6, 65.6)	(51.1, 56.4, 61.5)	(61.0, 67.6, 73.2)
Hamstrings (ft·lbs)	(29.2, 34.5, 37.9)	(27.9, 33.6, 39.4)	(34.8, 38.2, 42.5)
Vertical Jump (cm)	(14.0, 15.8, 17.0)	(14.0, 15.5, 17.0)	(17.0, 19.7, 21.0)