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SEX-RELATED DIFFERENCES IN JOINT-ANGLE-SPECIFIC FUNCTIONAL HAMSTRING TO QUADRICEPS STRENGTH RATIOS

Abstract

Purpose: To examine and compare sex-related differences in the functioning of the hamstrings and quadriceps muscles and the isokinetic hamstrings eccentric to quadriceps concentric functional ratio (H/Q_{FUNC}) .

Methods: Fifty male and 46 female young adults completed this study. Each participant carried out an isokinetic assessment to determine isokinetic concentric and eccentric torques during knee extension and flexion actions at 3 different angular velocities (60, 180 and 300º/s) adopting a lying position. The H/Q_{FUNC} was calculated using peak torque (PT) values and 3 different joint angle-specific torque values (15º, 30º, and 45º of knee extension). A repeated measures analysis of variance was used to compare the results and post hoc analyses using a Friedman correction were employed.

Results: There were statistically significant effects of angular velocity, joint angle and sex for the H/Q_{FUNC} ($p<0.01$). Thus, the H/Q_{FUNC} ratio in both males and females decreases closer to full knee extension and with increasing movement velocity. The H/Q_{FUNC} was also significantly lower in females compared to males, irrespective of moment velocity and joint angle.

Conclusions: The findings of the current study reinforce the need to examine the H/Q_{FUNC} ratio closer to full knee extension (where knee injury is most likely to occur) rather than using PT values which may not be as informative; as well as to focus preventive and rehabilitation training programmes on reducing quadriceps dominance by enhancing eccentric hamstring strength (especially in females who are at higher risk of injury).

Level of evidence III

Key words: isokinetic, injury prevention, strength, torque, anterior cruciate ligament.

Introduction

Hamstrings and knee injuries (i.e. non-contact anterior cruciate ligament tears [ACL]) are two of the most common injuries in sports involving activities with a high intensity of stretch-shortening cycles (i.e. soccer, rugby and volleyball) [4,20,25,37]. Biomechanical studies have indicated that hamstring strains are more prone to occur during the later part of the swing phase of sprinting (closer to full knee extension) when the hamstrings are exercising eccentrically (energy absorption) to decelerate the knee extension movement (generated among others by the concentric action of the quadriceps muscles) before foot contact, that is, as the muscle develops maximal tension while lengthening to stabilise the knee joint [42,43,47]. On the other hand, ACL tears tend to occur during dynamic movements such as landing from a jump and cutting as a result of insufficient dynamic stability of the tibiofemoral joint, which fails to prevent posterior dislocation of the femur on the tibia (anterior translation) [26]. Muscles that span the knee joint, such as the hamstrings and quadriceps play a crucial role in affecting anterior tibial translation and ACL strain [26]. Numerous studies have shown that the quadriceps act to increase anterior tibial translation (particularly with the knee close to full extension) and hence ACL strain (i.e. they are an ACL antagonist), while the hamstrings are considered an ACL agonist, restraining anterior tibial translation and reducing ACL strain [33,34,40].

It has therefore been postulated that a reciprocal hamstring to quadriceps strength imbalance may be considered a major risk factor for hamstrings strains and knee injuries [10,45].. However, despite the abundant literature dedicated to the topic, currently the use of reciprocal hamstring to quadriceps ratios to predict knee or hamstring injuries remains controversial, with some studies reporting a significant correlation between reciprocal hamstring to quadriceps ratios and hamstrings or ACL injury [10,11,28,30,32,36,44,45] in contrast with others that did not find any association [6,48]. Perhaps a possible explanation for this lack of scientific evidence could be attributed to insufficient ecological validity of the isokinetic methodologies that have been used to calculate reciprocal hamstring to quadriceps ratios and that describe the function of the knee. Most of the studies, although not all [15,18], that have examined the relationship between hamstring to quadriceps ratios and the likelihood of sustaining a hamstring or ACL injury, have employed isokinetic protocols with the participants adopting a seated position (80–110º hip flexion). This seated position is not representative of the hip position during sporting tasks (i.e. sprinting, landing, cutting) and does not replicate knee flexor and extensor muscle length-tension relationships that occur in the late phase of sprinting [48,47] as well as in the landing phase of a jump [22]; the most hazardous and prone situations to develop a hamstring [31,48,47] and ACL [20,23] injury respectively. Furthermore, the reciprocal hamstrings to quadriceps ratios have been routinely quantified by dividing the eccentric peak torque of the knee flexors (hamstrings) and concentric peak torque of the extensors (quadriceps) and referred to as functional hamstring to quadriceps strength ratio (H/Q_{FUNC}). Peak concentric and eccentric torque production is likely to occur in the mid-late range of the movement (around 40–80° of knee flexion) [19], whereas it is well recognized that injury is likely to occur when the knee is closer to full extension (0–40°) [23,31]. Thus, although the H/Q_{FUNC} appears to reflect the reciprocal antagonistic function of the muscles during sporting activities such as sprinting and landing [2,3,39], this joint angle discrepancy inherent within any peak torque ratio may reduce the validity of the H/Q_{FUNC} to assess the muscular balance of the knee. Few studies (to the authors´ knowledge) appear to have examined the angle specific H/Q_{FUNC} ratio using small sample sizes and only in males [1,2,18,29]. These studies have reported an increase in the H/Q_{FUNC} as the knee approaches full extension [1,2,18,29].

Therefore, there is a clear lack of studies that describe the muscular control of the knee using a more ecologically valid isokinetic protocol (e.g. by calculating the H/Q_{FUNC} using angle specific torque values close to full extension with participants adopting a hip position of 10-20º of flexion). This knowledge might enhance current screening methods and help to: identify the normal function of the knee by which pathogenic states can be compared; monitor rehabilitation programmes; and determine whether an athlete can safely return to sport. In addition, the study of the possible sex-related differences in H/Q_{FUNC} ratio may help to identify the mechanisms through which women sustain more knee injuries than men.

Therefore, the main purpose of this study was to examine and compare the functioning of the hamstrings and quadriceps muscles and the H/Q_{FUNC} ratio calculated using peak torque values, 3 different joint angle-specific torque values (15°, 30° and 45° of knee extension) and 3 different angular velocities (60, 180 and 300º/s) adopting a lying position (10-20º of hip flexion) as well as to determine the possible sex-related differences.

Materials and Methods

Participants

One hundred and four participants, consisting of 52 males and 52 females took part in the current study. The exclusion criteria were: (1) histories of orthopaedic problems, such as episodes of hamstrings and knee injuries, fractures, surgery or pain in the spine and/or hamstrings and quadriceps muscles over the past six months; (2) presence of self-reported delayed onset muscle soreness at the testing session and (3) female participants were not in the ovulation phase (self-reported; days 10-14) of their menstrual cycle during testing to account for fluctuating concentrations of oestrogen throughout the menstrual cycle affecting musculotendonous stiffness and joint laxity [5,17]. The participants were verbally informed about the study procedures before testing and provided written informed consent.

Fifty males (age = 27.9 ± 3.8 years; stature = 181.3 ± 7.4 cm; body mass = 79.2 ± 6.7 kg) and 46 females (age = 26.9 ± 5.2 years; stature = 159.7 ± 7.3 cm; body mass = 67.7 ± 9.5 kg) completed this study. Two men and 6 women were excluded from the study because they missed the testing session (3 women) or did not complete the entire testing procedure due to time restriction (2 men and 3 women). Participants were categorised using the International

Physical Activity Questionnaire Short Format [8] as all having moderate (17 men and 8 women) to low (33 men and 38 women) habitual levels of physical activity with a score of 675 ±423 MET-mins.week^{-1}.

Isokinetic testing procedure

A week before the testing session commenced, all participants carried out a familiarisation session. Practice included anthropometry (body mass and stature) followed by habituation to the isokinetic test procedure that was completed during the experimental session.

In the experimental session, participants began by completing a 10-min standardized warm-up (cycling at 90 W for men and 60 W for women at 60–70 rpm) and 5-min standardized dynamic stretching exercises. After this general warm-up, the participants performed a specific isokinetic warm-up consisting of 3 sub-maximal (self-perceived 50% effort) and 2 maximal concentric and eccentric knee extension and flexion actions at 120º/s.

The isokinetic assessment was carried out 2-3 minutes after the entire warm-up was completed. A Biodex System-3 Isokinetic dynamometer (Biodex Corp., Shirley, NY, USA) and its respective manufacture software were used to determine isokinetic concentric and eccentric torques during knee extension and flexion actions. Only the dominant leg was tested as not meaningful differences between legs have been previously reported for sedentary and recreationally active adults [15,27]. The dynamometer was calibrated according to the manufacturer’s instructions immediately before each test session and verified immediately after to ensure that no changes occurred in sensitivity. The verification procedure was conducted using known weights to assess the reliability of torque, velocity and position measurement [16]. Participants were secured supine (concentric knee extension actions) and prone (eccentric knee flexion actions) on the dynamometer with the hip passively flexed at 10-20º . The axis of rotation of the dynamometer lever arm was aligned with the lateral epicondyle of the knee. The force pad was placed approximately 3 cm superior to the medial malleolus with the foot in a relaxed position. Adjustable strapping across the pelvis, thigh proximal to the knee and foot localised the action of the musculature involved. The range of movement was set from 90° knee flexion (starting position) to 0° (0º was determined as maximal voluntary knee extension for each participant). The rationale of determining the range of movement throughout the individuals' voluntary muscle activation ability to full extend the knee was based on the findings found in a pilot study with ten participants (5 males and 5 females) different than those selected for the current study. For this purpose, an electrogoniometer (SG150, Biometrics Ltd., Gwent, UK; pre-amplified lead, Noraxon, Scottsdale, USA) was attached to either side of the lateral aspect of the knee and used to identify whether the different effects of gravity associated with the two different testing positions used in the isokinetic assessment (prone: gravity actively assists knee extension [hyperextension]; supine: gravity actively resists knee extension [restriction]) may affect the participants' ability to voluntary extend their knee to full extension. Signals were sampled at 2000 Hz and transferred to Spike 2 simultaneously with the force signals via the same A/D converter. No meaningful differences in the participants' ability to reach knee full extension values between testing positions (prone vs supine) were found (range: 0º to 4º).

The isokinetic examination was separated into 2 parts. The first part of the examination was the assessment of the concentric knee extension torque (quadriceps) with participants adopting a supine position. After a 5 min rest period, the isolate eccentric knee flexion torque (hamstring) assessment was performed with participants in a prone position. After each concentric and eccentric knee flexion and extension muscle action, the participant´s active limb was passively returned to the starting position.

The rationale of using a prone position to assess the eccentric knee flexion torque instead of the supine position to assess concentric knee extension torque was based on the pilot data where participants reported the prone position as being more comfortable. The same pilot study showed that participants could not maintain the required torque output throughout the range of motion in the reactive eccentric mode, subsequently causing stalling of the lever arm. Therefore, the passive eccentric mode was chosen so that the full range of movement would be completed for every action, which is important for the calculation of the H/Q_{FUNC} ratio using joint angle-specific torque values.

In both testing methods, 3 repetitions of each knee muscle action were performed at 3 present constant angular velocities in the following order: 60, 180 and 300º/s (slow to fast). Participants rested for 1 min between each repetition to allow for full musculoskeletal recovery. The number of maximal muscle actions and the rest period durations were chosen to minimise musculoskeletal fatigue, which is unlikely to occur (based on the participants' perceptions reported in the pilot study) with only three muscle actions at three velocities (60, 180 and 300º/s) and a 1 min rest between muscle actions and velocities and 5 min rest between testing modes (concentric and eccentric).

For both concentric and eccentric actions, participants were encouraged to push-pull/resist as hard and as fast as possible and to complete the full range of motion. Participants were insructed to abort the test if they felt any discomfort or pain. During the test, all participants were given visual feedback from the system monitor. They were also verbally encouraged by the investigator to give their maximal effort, and the instructions were standardised by using key words such as "resist", "push" and "hard and fast as possible".

Measures

The concentric quadriceps (figure 1) and eccentric hamstrings (figure 2) torque-angle curves at each velocity (60º/s, 180º/s and 300º/s) were determined using specific single angle torque values (15º, 30º, 45º, 50º, 55º; 60º, 65º, 70º, 75º. 80º, 85º, 90º). However, only four different gravity-corrected torque values (peak torque generated during the isokinetic load range phase and 3 joint angle-specific torque values [15°, 30° and 45° of knee extension]) were extracted for each of the 3 trials performed at each velocity (60°/s, 180°/s and 300°/s) and used for statistical analysis.

For each isokinetic torque variable, the mean of the 3 trials at each velocity was used for subsequent statistical analysis due to the magnitude of the error component decreasing with increased trials [35,38]. In addition, Sole et al. [41] reported better reproducibility when using the mean value from 3 trials rather than a maximum value from 3 repetitions. Thus, the H/Q_{FUNC} ratios were calculated as the ratio between the torques produced eccentrically by the knee flexors and concentrically by the knee extensors.

Before data collection and within the above-mentioned pilot study, the inter-session reliability of all variables using the procedure just described was determined using a test-retest design. The isokinetic testing procedure was carried out twice within a one-week interval. An intraclass correlation coefficient (ICC_{2k}) and a coefficient of variation (standard error of measurement expressed as a percentage [CV]) were calculated from the results of subsequent measurements. Results of the two testing sessions showed moderate reliability scores for all the measures (ICC ranged from 0.81 to 0.95 and CV < 15%), which was consistent with previous studies [30,41].

This study was approved by the Mansoura University Research Ethics Committee (DPS.SAID.01.2014).

Statistical Analysis

Data were analysed using SPSS for Windows (version 18.0, SPSS, Inc., Chicago, IL, USA). Descriptive statistics including means and standard deviations were calculated for each variable. A repeated measures analysis of variance (ANOVA) was used to compare the results and post hoc analyses using a Bonferroni correction were employed. The significance level was set to 0.05.

Based on pilot data, a statistical sample size calculation was performed using the software package, G*Power 3.1.2. A minimum sample size of 42 participants for each sex (males and female) was deemed necessary to achieve a statistical power of 80% for the outcome measure that reported the worst test-retest reliability scores (i.e. H/Q_{FUNC} at 15º of knee extension and measured at 300º/s). The current study initially recruited 52 participants of each sex-category to ensure that the appropriate number of participants would complete the study, even with some attrition.

Results

For both concentric quadriceps and eccentric hamstring muscle actions, peak and angle-specific (45°, 30° and 15° of knee extension) isokinetic torque values decreased significantly with increasing angular velocity in both men (Hamstrings, $p<0.01$; Quadriceps, $P<0.01$) and women (Hamstrings, $p<0.01$; Quadriceps, $P<0.01$). In addition, significant sex-related differences were found, with female displaying lower torque values than their males counterparts at each angular velocity and muscle action ($p<0.001$).

[Insert Figure 1 and 2 here]

H/Q_{FUNC} ratios (Figure 3) decreased significantly with increasing angular velocity in both men ($P<0.01$) and women ($P<0.01$). Post hoc analysis revealed that H/Q_{FUNC} ratios at 60/s were higher than those at all other angular velocities, and that H/Q_{FUNC} ratios at 180°/s were higher than at 300°/s ($p<0.01$). Comparison of H/Q_{FUNC} ratios revealed significant differences between males and females ($p<0.01$), whereby H/Q_{FUNC} ratios are greater in males at angular velocities of 60, 180 and 300/s. H/Q_{FUNC} ratios at three different KE-angles, 45°, 30° and 15°, measured at angular velocities of 60, 180 and 300/s are illustrated in Figure 4. Friedman analysis reveals an effect for KE-angles at each angular velocity ($p<0.01$). Post hoc analysis revealed the lowest H/Q_{FUNC} ratio exist at a KE-angle of 15° which was significantly different to all other angles, while the H/Q_{FUNC} ratio at 30° is also significantly different to that at 45°. A main effect for sex is also evident ($p<0.01$) as post hoc analysis revealed significantly different men and women

H/Q_{FUNC} ratios at each KE-angle and angular velocity, such that women display a reduced H/Q_{FUNC} ratio in each condition (KE-angle and velocity) ($p<0.01$).

[Insert Figure 3 and 4 near here]

Discussion

The most important finding of the present study was the presence of statistically significant effects of angular velocity, joint angle and sex for the H/Q_{FUNC}. These data indicate that the H/Q_{FUNC} ratio in both males and females decreases closer to full knee extension and with increasing movement velocity. The H/Q_{FUNC} was also significantly lower in females compared to males, irrespective of moment velocity and joint angle, suggesting reduced muscular control in females compared with males. To our knowledge, this is the first study to have reported significant sex differences in the H/Q_{FUNC} using an angle specific ratio with the hip extended (10-20 degrees). By using angle specific data we have been able to demonstrate that the sex difference in muscular control remain as the knee joint moves towards full knee extension. This is attributed to lower eccentric torque production of hamstring muscles compared with concentric torque production of quadriceps muscles as the knee extends in females. ~~It is difficult to compare our findings to previously published literature as previous studies have failed to explore sex differences in the H/Q_{FUNC} using angle specific torque values where injury is most likely to occur; or have determined torque in a seated position with the hip flexed; and therefore may be determined as not being directly comparable [12,29].~~

In contrast to previous studies [1,2,18,19] ~~(REFS??)~~, we found a significant reduction in the H/Q_{FUNC} as knee moves towards full knee extension, irrespective of sex. These findings are important as at near full knee extension, static stability is reduced and functional stability relies mainly on muscular control to protect the knee structures [20]. The data showing that muscular dynamic knee control is compromised as the joint approaches full extension reinforces the inappropriate use of using peak torque to calculate the H/Q_{FUNC} ratio. By observing the change in the angle-specific H/Q_{FUNC} ratio, we have shown that the eccentric hamstring muscle action is less effective in extended knee positions where injury is most likely to occur. These findings have particular implications for sports that include common movement patterns that place the knee in extended positions (eg cutting, landing, kicking)..

The reason we may have found differences compared to the Kellis and Katis [29] study is that they averaged torque over 10° portions of the movement whereas in this study we used a single angle specific torque value. Differences may also be attributed to the populations used in each study, Kellis and Katis [29] investigated pubertal children while we looked at recreational adults. Testing in the Kellis and Katis [29] study was also conducted in a seated position and we have previously reported that the H/Q_{FUNC} is significantly higher in seated versus a supine position ~~by as much as 21% at higher movement velocities (300°/s)~~ [14]. However, it is also possible that the lower H/Q_{FUNC} in more extended knee positions may be due to participants not fully resisting the lever arm to the extremes of the range of movement during eccentric testing. The study design attempted to reduce this by instructing participants to resist the lever arm throughout the entire range of movement and participants were also habituated in the familiarisation session.

~~It is widely accepted in the literature that a H/Q_{FUNC} ratio outside the 0.7-1 range suggests an increased injury risk [12]. It is important to consider that the H/Q_{FUNC} of 1.0, cited as being representative of producing 'adequate' knee stability is based on a value determined using PT and thus likely from the mid-range of movement [3].~~ The low functional ratios scores (b~~of~~ ~~b~~elow 1.0) reported for both males and females in the current study may also be attributed to the inability to recruit the entire motor unit pool during eccentric actions. According to the current findings, injury occurrence in females may be due to a specific hamstring weakness with the H/Q_{FUNC} decreasing when approaching full knee extension and with increasing angular velocity. This would represent the inability of the hamstrings to absorb the anterior tibial forces induced by the concentric quadriceps action. This has implications for dynamic knee stability near full knee extension and reinforces the need to examine the ratio closer to full knee extension where it is most relevant and not to use PT values, especially in females.

The findings of the current study demonstrate that the H/Q_{FUNC} decreases with increasing movement velocity irrespective of joint angle and sex. These data are in contrast to some previously reported studies that have shown a significant increase in the H/Q_{FUNC} with increasing movement velocity [13,29]. This increase in the H/Q_{FUNC} with movement velocity is attributed to the decline in concentric torque production compared with the relatively stable eccentric torque production during increasing movement velocity, linked to the binding and interaction of actin and myosin within the muscle sarcomere. It is not clear why we found a reduction in the H/Q_{FUNC} with increasing movement velocity but it may be attributed to the hip position used during testing, changing the length tension relationship, or the fact that we are not using PT to determine the ratio. Indeed, the classic torque-velocity relationship is based on maximal torque production and it remains to be established if the same relationship holds for angle specific torque.

Previous studies have demonstrated significant differences in H/Q_{FUNC} ratio between males and females [9,24,46]. The findings of the current study support previous observations which have reported a higher H/Q_{FUNC} ratio in males compared with females, albeit using PT data. This may be due to the more powerful quadriceps muscles compared to the hamstrings muscles in females (Quadriceps dominance) or may be due to the greater contribution of the hamstrings of males than females in the control of running activities and for stabilizing the joint angle during foot contact with the ground. ~~There are some conflicting data which have reported a similar H/Q_{FUNC} ratio between elite male and female athletes but this is in the minority [7]..The uncertainty in the literature regarding sex differences in the H/Q_{FUNC} ratio may be related to the~~

~~different age ranges, angular velocities, hip position, sample sizes and training background of participants.~~

One of the potential limitations of the current study is the population used. The age distribution of participants and their physical activity status were relatively narrow and the generalizability to other populations (i.e. athletes) cannot be ascertained. In addition, the testing modes and angular velocities were also presented to all subjects in a systematic order without randomization, as a previous study measuring knee extension torque at multiple angles showed no effect of fatigue or learning [21]. The main effects of mode and angular velocity on joint torque and H/Q ratio in our study are also comparable to many other studies. The order of testing would not have affected any sex-related differences in H/Q_{FUNC} measurements. Thus, ~~we believe~~ the lack of randomization in the experimental protocol might ~~has~~have had a minimal effect on our results.

Conclusions

The current study provides clinically relevant information regarding the muscular control of the knee by using a more functionally relevant isokinetic approach to calculate the H/Q_{FUNC} that might enhance current screening methods and help to identify athletes at high risk of injury. ~~This method may also aid the design and monitoring of both preventive and rehabilitation programmes.~~ In this sense, the data reports that the H/Q_{FUNC} ratio decreases closer to full knee extension and with increasing movement velocity, irrespective of sex.~~,~~ The H/Q_{FUNC} was also significantly lower in females compared to males irrespective of moment velocity and joint angle. ~~By observing the change in the angle-specific H/Q_{FUNC} ratio~~In addition, we have shown that the eccentric hamstring muscle action is less effective in extended knee positions. ~~In addition, the H/Q_{FUNC} was also significantly lower in females compared to males irrespective of moment velocity and joint angle~~. These findings reinforce the need: (a) to examine the H/Q_{FUNC} ratio closer to full knee extension (where knee injury is most likely to occur) and not to use PT values; as well as (b) to focus preventive and rehabilitation training programmes on reducing quadriceps dominance and enhance eccentric hamstring strength by using, among other, long-length eccentric exercises. This is especially relevant in females, a population at higher risk of injury.

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Figure legends

~~Figure 1. Isokinetic testing assessment (left: concentric knee extension torque [quadriceps]; right: eccentric knee flexion torque [hamstrings].~~

Figure 1~~2~~. Quadriceps concentric angle-specific toque curve for male (dashed line) and females (straight line) at: A) 60°/s, B) 180°/s and C) 300°/s. The peak and 3 angle-specific (45°, 30° and 15° of knee extension) torque values are specifically highlighted in both males (open squares and females (filled squares). * significant torque-related differences detected by post-hoc analysis ($p<0.01$). T: significant sex-related differences detected by post-hoc analysis ($p<0.01$).

Figure 2~~3~~. Hamstrings eccentric angle-specific toque curve for male (dashed line) and females (straight line) at: A) 60°/s, B) 180°/s and C) 300°/s. The peak and 3 angle-specific (45°, 30° and 15° of knee extension) torque values are specifically highlighted in both males (open squares and females (filled squares). * significant torque-related differences detected by post-hoc analysis ($p<0.01$). T: significant sex-related differences detected by post-hoc analysis ($p<0.01$).

Figure 3~~4~~. Functional hamstring to quadriceps strength ratios calculated using peak torque values.

Figure 45. Functional hamstring to quadriceps strength ratios calculated at 3 different joint angle-specific torque values (15, 30 and 45º of knee extension).