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

3 **Abstract**

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

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

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

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

23 Level of evidence III

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

25 **Introduction**

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

42 It has therefore been postulated that a reciprocal hamstring to quadriceps strength imbalance
43 may be considered a major risk factor for hamstrings strains and knee injuries [10,45]..
44 However, despite the abundant literature dedicated to the topic, currently the use of reciprocal
45 hamstring to quadriceps ratios to predict knee or hamstring injuries remains controversial, with
46 some studies reporting a significant correlation between reciprocal hamstring to quadriceps
47 ratios and hamstrings or ACL injury [10,11,28,30,32,36,44,45] in contrast with others that did
48 not find any association [6,48]. Perhaps a possible explanation for this lack of scientific
49 evidence could be attributed to insufficient ecological validity of the isokinetic methodologies

50 that have been used to calculate reciprocal hamstring to quadriceps ratios and that describe the
51 function of the knee. Most of the studies, although not all [15,18], that have examined the
52 relationship between hamstring to quadriceps ratios and the likelihood of sustaining a hamstring
53 or ACL injury, have employed isokinetic protocols with the participants adopting a seated
54 position (80–110° hip flexion). This seated position is not representative of the hip position
55 during sporting tasks (i.e. sprinting, landing, cutting) and does not replicate knee flexor and
56 extensor muscle length-tension relationships that occur in the late phase of sprinting [48,47] as
57 well as in the landing phase of a jump [22]; the most hazardous and prone situations to develop
58 a hamstring [31,48,47] and ACL [20,23] injury respectively. Furthermore, the reciprocal
59 hamstrings to quadriceps ratios have been routinely quantified by dividing the eccentric peak
60 torque of the knee flexors (hamstrings) and concentric peak torque of the extensors (quadriceps)
61 and referred to as functional hamstring to quadriceps strength ratio (H/Q_{FUNC}). Peak concentric
62 and eccentric torque production is likely to occur in the mid-late range of the movement (around
63 40–80° of knee flexion) [19], whereas it is well recognized that injury is likely to occur when
64 the knee is closer to full extension (0–40°) [23,31]. Thus, although the H/Q_{FUNC} appears to
65 reflect the reciprocal antagonistic function of the muscles during sporting activities such as
66 sprinting and landing [2,3,39], this joint angle discrepancy inherent within any peak torque ratio
67 may reduce the validity of the H/Q_{FUNC} to assess the muscular balance of the knee. Few studies
68 (to the authors' knowledge) appear to have examined the angle specific H/Q_{FUNC} ratio using
69 small sample sizes and only in males [1,2,18,29]. These studies have reported an increase in
70 the H/Q_{FUNC} as the knee approaches full extension [1,2,18,29].

71 Therefore, there is a clear lack of studies that describe the muscular control of the knee using a
72 more ecologically valid isokinetic protocol (e.g. by calculating the H/Q_{FUNC} using angle specific
73 torque values close to full extension with participants adopting a hip position of 10-20° of
74 flexion). This knowledge might enhance current screening methods and help to: identify the

75 normal function of the knee by which pathogenic states can be compared; monitor rehabilitation
76 programmes; and determine whether an athlete can safely return to sport. In addition, the study
77 of the possible sex-related differences in H/Q_{FUNC} ratio may help to identify the mechanisms
78 through which women sustain more knee injuries than men.

79 Therefore, the main purpose of this study was to examine and compare the functioning of the
80 hamstrings and quadriceps muscles and the H/Q_{FUNC} ratio calculated using peak torque values,
81 3 different joint angle-specific torque values (15° , 30° and 45° of knee extension) and 3
82 different angular velocities (60, 180 and $300^\circ/\text{s}$) adopting a lying position ($10\text{-}20^\circ$ of hip flexion)
83 as well as to determine the possible sex-related differences.

84 **Materials and Methods**

85 **Participants**

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

95 Fifty males (age = 27.9 ± 3.8 years; stature = 181.3 ± 7.4 cm; body mass = 79.2 ± 6.7 kg) and
96 46 females (age = 26.9 ± 5.2 years; stature = 159.7 ± 7.3 cm; body mass = 67.7 ± 9.5 kg)
97 completed this study. Two men and 6 women were excluded from the study because they
98 missed the testing session (3 women) or did not complete the entire testing procedure due to
99 time restriction (2 men and 3 women). Participants were categorised using the International

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

103 Isokinetic testing procedure

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

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

112 The isokinetic assessment was carried out 2-3 minutes after the entire warm-up was completed.

113 A Biodex System-3 Isokinetic dynamometer (Biodex Corp., Shirley, NY, USA) and its
114 respective manufacture software were used to determine isokinetic concentric and eccentric
115 torques during knee extension and flexion actions. Only the dominant leg was tested as not
116 meaningful differences between legs have been previously reported for sedentary and
117 recreationally active adults [15,27]. The dynamometer was calibrated according to the
118 manufacturer's instructions immediately before each test session and verified immediately after
119 to ensure that no changes occurred in sensitivity. The verification procedure was conducted
120 using known weights to assess the reliability of torque, velocity and position measurement [16].

121 Participants were secured supine (concentric knee extension actions) and prone (eccentric knee
122 flexion actions) on the dynamometer with the hip passively flexed at 10-20° . The axis of
123 rotation of the dynamometer lever arm was aligned with the lateral epicondyle of the knee. The
124 force pad was placed approximately 3 cm superior to the medial malleolus with the foot in a

125 relaxed position. Adjustable strapping across the pelvis, thigh proximal to the knee and foot
126 localised the action of the musculature involved. The range of movement was set from 90° knee
127 flexion (starting position) to 0° (0° was determined as maximal voluntary knee extension for
128 each participant). The rationale of determining the range of movement throughout the
129 individuals' voluntary muscle activation ability to full extend the knee was based on the
130 findings found in a pilot study with ten participants (5 males and 5 females) different than those
131 selected for the current study. For this purpose, an electrogoniometer (SG150, Biometrics Ltd.,
132 Gwent, UK; pre-amplified lead, Noraxon, Scottsdale, USA) was attached to either side of the
133 lateral aspect of the knee and used to identify whether the different effects of gravity associated
134 with the two different testing positions used in the isokinetic assessment (prone: gravity actively
135 assists knee extension [hyperextension]; supine: gravity actively resists knee extension
136 [restriction]) may affect the participants' ability to voluntary extend their knee to full extension.
137 Signals were sampled at 2000 Hz and transferred to Spike 2 simultaneously with the force
138 signals via the same A/D converter. No meaningful differences in the participants' ability to
139 reach knee full extension values between testing positions (prone vs supine) were found (range:
140 0° to 4°).

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

147 The rationale of using a prone position to assess the eccentric knee flexion torque instead of the
148 supine position to assess concentric knee extension torque was based on the pilot data where
149 participants reported the prone position as being more comfortable. The same pilot study

150 showed that participants could not maintain the required torque output throughout the range of
151 motion in the reactive eccentric mode, subsequently causing stalling of the lever arm.
152 Therefore, the passive eccentric mode was chosen so that the full range of movement would be
153 completed for every action, which is important for the calculation of the H/Q_{FUNC} ratio using
154 joint angle-specific torque values.

155 In both testing methods, 3 repetitions of each knee muscle action were performed at 3 present
156 constant angular velocities in the following order: 60, 180 and 300°/s (slow to fast). Participants
157 rested for 1 min between each repetition to allow for full musculoskeletal recovery. The number
158 of maximal muscle actions and the rest period durations were chosen to minimise
159 musculoskeletal fatigue, which is unlikely to occur (based on the participants' perceptions
160 reported in the pilot study) with only three muscle actions at three velocities (60, 180 and
161 300°/s) and a 1 min rest between muscle actions and velocities and 5 min rest between testing
162 modes (concentric and eccentric).

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

169 Measures

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

175 for each of the 3 trials performed at each velocity (60°/s, 180°/s and 300°/s) and used for
176 statistical analysis.

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

183 Before data collection and within the above-mentioned pilot study, the inter-session reliability
184 of all variables using the procedure just described was determined using a test-retest design.

185 The isokinetic testing procedure was carried out twice within a one-week interval. An intraclass
186 correlation coefficient (ICC_{2k}) and a coefficient of variation (standard error of measurement
187 expressed as a percentage [CV]) were calculated from the results of subsequent measurements.

188 Results of the two testing sessions showed moderate reliability scores for all the measures (ICC
189 ranged from 0.81 to 0.95 and CV < 15%), which was consistent with previous studies [30,41].

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

192 Statistical Analysis

193 Data were analysed using SPSS for Windows (version 18.0, SPSS, Inc., Chicago, IL, USA).

194 Descriptive statistics including means and standard deviations were calculated for each
195 variable. A repeated measures analysis of variance (ANOVA) was used to compare the results
196 and post hoc analyses using a Bonferroni correction were employed. The significance level was
197 set to 0.05.

198 Based on pilot data, a statistical sample size calculation was performed using the software
199 package, G*Power 3.1.2. A minimum sample size of 42 participants for each sex (males and

200 female) was deemed necessary to achieve a statistical power of 80% for the outcome measure
201 that reported the worst test-retest reliability scores (i.e. H/Q_{FUNC} at 15° of knee extension and
202 measured at $300^\circ/\text{s}$). The current study initially recruited 52 participants of each sex-category
203 to ensure that the appropriate number of participants would complete the study, even with some
204 attrition.

205 **Results**

206 For both concentric quadriceps and eccentric hamstring muscle actions, peak and angle-specific
207 (45° , 30° and 15° of knee extension) isokinetic torque values decreased significantly with
208 increasing angular velocity in both men (Hamstrings, $p < 0.01$; Quadriceps, $P < 0.01$) and women
209 (Hamstrings, $p < 0.01$; Quadriceps, $P < 0.01$). In addition, significant sex-related differences were
210 found, with female displaying lower torque values than their males counterparts at each angular
211 velocity and muscle action ($p < 0.001$).

212 [Insert Figure 1 and 2 here]

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

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

226 [Insert Figure 3 and 4 near here]

227 Discussion

228 The most important finding of the present study was the presence of statistically significant
229 effects of angular velocity, joint angle and sex for the H/Q_{FUNC}. These data indicate that the
230 H/Q_{FUNC} ratio in both males and females decreases closer to full knee extension and with
231 increasing movement velocity. The H/Q_{FUNC} was also significantly lower in females compared
232 to males, irrespective of moment velocity and joint angle, suggesting reduced muscular control
233 in females compared with males. To our knowledge, this is the first study to have reported
234 significant sex differences in the H/Q_{FUNC} using an angle specific ratio with the hip extended
235 (10-20 degrees). By using angle specific data we have been able to demonstrate that the sex
236 difference in muscular control remain as the knee joint moves towards full knee extension. This
237 is attributed to lower eccentric torque production of hamstring muscles compared with
238 concentric torque production of quadriceps muscles as the knee extends in females. ~~It is difficult
239 to compare our findings to previously published literature as previous studies have failed to
240 explore sex differences in the H/Q_{FUNC} using angle specific torque values where injury is most
241 likely to occur; or have determined torque in a seated position with the hip flexed; and therefore
242 may be determined as not being directly comparable [12,29].~~

243 In contrast to previous studies [1,2,18,19] (REFS??), we found a significant reduction in the
244 H/Q_{FUNC} as knee moves towards full knee extension, irrespective of sex. These findings are
245 important as at near full knee extension, static stability is reduced and functional stability relies
246 mainly on muscular control to protect the knee structures [20]. The data showing that muscular
247 dynamic knee control is compromised as the joint approaches full extension reinforces the
248 inappropriate use of using peak torque to calculate the H/Q_{FUNC} ratio. By observing the change

249 in the angle-specific H/Q_{FUNC} ratio, we have shown that the eccentric hamstring muscle action
250 is less effective in extended knee positions where injury is most likely to occur. These findings
251 have particular implications for sports that include common movement patterns that place the
252 knee in extended positions (eg cutting, landing, kicking)..

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

265 ~~It is widely accepted in the literature that a H/Q_{FUNC} ratio outside the 0.7-1 range suggests an~~
266 ~~increased injury risk [12]. It is important to consider that the H/Q_{FUNC} of 1.0, cited as being~~
267 ~~representative of producing ‘adequate’ knee stability is based on a value determined using PT~~
268 ~~and thus likely from the mid-range of movement [3].~~ The low functional ratios scores (below
269 1.0) reported for both males and females in the current study may also be attributed to
270 the inability to recruit the entire motor unit pool during eccentric actions. According to the
271 current findings, injury occurrence in females may be due to a specific hamstring weakness
272 with the H/Q_{FUNC} decreasing when approaching full knee extension and with increasing angular
273 velocity. This would represent the inability of the hamstrings to absorb the anterior tibial forces

274 induced by the concentric quadriceps action. This has implications for dynamic knee stability
275 near full knee extension and reinforces the need to examine the ratio closer to full knee
276 extension where it is most relevant and not to use PT values, especially in females.

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

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

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

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

310 **Conclusions**

311 The current study provides clinically relevant information regarding the muscular control of the
312 knee by using a more functionally relevant isokinetic approach to calculate the H/Q_{FUNC} that
313 might enhance current screening methods and help to identify athletes at high risk of injury.
314 ~~This method may also aid the design and monitoring of both preventive and rehabilitation~~
315 ~~programmes.~~ In this sense, the data reports that the H/Q_{FUNC} ratio decreases closer to full knee
316 extension and with increasing movement velocity, irrespective of sex. The H/Q_{FUNC} was also
317 significantly lower in females compared to males irrespective of moment velocity and joint
318 angle. ~~By observing the change in the angle specific H/Q_{FUNC} ratio~~ In addition, we have shown
319 that the eccentric hamstring muscle action is less effective in extended knee positions. ~~In~~
320 ~~addition, the H/Q_{FUNC} was also significantly lower in females compared to males irrespective~~
321 ~~of moment velocity and joint angle.~~ These findings reinforce the need: (a) to examine the
322 H/Q_{FUNC} ratio closer to full knee extension (where knee injury is most likely to occur) and not

323 to use PT values; as well as (b) to focus preventive and rehabilitation training programmes on
324 reducing quadriceps dominance and enhance eccentric hamstring strength by using, among
325 other, long-length eccentric exercises. This is especially relevant in females, a population at
326 higher risk of injury.

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453 **Figure legends**

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

456 Figure 12. Quadriceps concentric angle-specific torque curve for male (dashed line) and females
 457 (straight line) at: A) 60°/s, B) 180°/s and C) 300°/s. The peak and 3 angle-specific (45°, 30° and
 458 15° of knee extension) torque values are specifically highlighted in both males (open squares
 459 and females (filled squares). * significant torque-related differences detected by post-hoc
 460 analysis (p<0.01). T: significant sex-related differences detected by post-hoc analysis (p<0.01).

461 Figure 23. Hamstrings eccentric angle-specific torque curve for male (dashed line) and females
 462 (straight line) at: A) 60°/s, B) 180°/s and C) 300°/s. The peak and 3 angle-specific (45°, 30° and
 463 15° of knee extension) torque values are specifically highlighted in both males (open squares
 464 and females (filled squares). * significant torque-related differences detected by post-hoc
 465 analysis (p<0.01). T: significant sex-related differences detected by post-hoc analysis (p<0.01).

466 Figure 34. Functional hamstring to quadriceps strength ratios calculated using peak torque
 467 values.

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

470