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Age related differences in functional hamstring/quadriceps ratio following soccer exercise in female youth players: An injury risk factor

Running header: muscular control and fatigue in female youth soccer

Abstract

Purpose: Fatigue negatively alters dynamic knee control and the functional hamstring/quadriceps ratio (H/Q_{FUNC}) plays an important role in stabilising the joint. The aim of this study was to investigate the influence of soccer specific exercise on H/Q_{FUNC} in U13, U15 and U17 year-old female soccer players. **Methods:** 36 female players performed concentric and eccentric actions of the hamstrings at 60, 120 and 180°/s before and after an age group specific field based soccer protocol. H/Q_{FUNC} was determined in the first 30° of knee flexion. **Results:** Significant angle x velocity ($p = 0.001$) and time x angle ($p = 0.033$) interaction effects were found indicating a lower H/Q_{FUNC} with increased movement velocity at 0-10° as opposed to greater knee flexion angles. Fatigue related effects were only evident near full knee extension. Probabilistic inferences indicated that changes in H/Q_{FUNC} were generally unclear in U13s, likely detrimental in U15s and very likely beneficial in U17s. **Conclusions:** Altered muscular control following soccer specific exercise is age dependent with players 1-year post peak height velocity at greatest risk of injury. Injury prevention and screening need to be age and maturation appropriate, should take into account the effects of fatigue, and include movements near full extension.

Keywords: muscular control, injury risk, fatigue, female, youth

INTRODUCTION

Injury risk increases throughout adolescence and appears to peak around peak height velocity (PHV) (30), and is associated with pubertal development (17). It is well recognised that when rapid, unanticipated movements and landing activities are performed, the medial and lateral hamstring muscles play a key role in stabilizing the knee joint and successfully counteracting the extreme load forces generated (29). Previous studies have reported a conventional hamstrings to quadriceps ratio (H/Q ratio) using only concentric actions, but these studies should not be viewed as functionally relevant, as co-contraction around the joint involves an eccentric and concentric muscle action (1). In order for the H/Q ratio to describe normal knee function and account for the agonist-antagonist relationship, the functional ratio (H/Q_{FUNC}) (eccentric hamstrings / concentric quadriceps torque) should be determined, as it is functionally relevant (1,6)

The few studies that have examined the H/Q_{FUNC} as a descriptor of muscular control of the knee joint have numerous study design flaws. Firstly, the importance of joint angle has been highlighted in epidemiological findings, which demonstrate that Anterior Cruciate Ligament (ACL) injury is most likely to occur near full knee extension (25). However, previous studies have calculated the H/Q_{FUNC} using peak torque (PT) values (2, 8) which occur in the mid range of joint movement and thus not at the joint angle where injury is most likely to occur. Additionally the joint angle where PT occurs for eccentric and concentric muscle actions is almost always different, and therefore using PT should not be used (8). To the authors' knowledge only one study on pubertal males has calculated the H/Q_{FUNC} at various angular positions, reporting an increase in the H/Q_{FUNC} as the knee approaches full extension (16). Given the high relative risk of ACL injury in adolescent females it is surprising that there are no comparable data on female youth athletes, and noticably no data using angle specific

values in relation to changes in the H/Q_{FUNC} after fatigue. Secondly, most studies appear to have determined torque in a seated position with the hip flexed ($80-90^\circ$). However, injury occurs with the hip extended, usually at about 10° of hip flexion, and thus data obtained in a flexed position should not be considered functionally relevant. Indeed one previous study has indicated that changing hip angle significantly alters the H/Q_{FUNC} , which is lower in a prone/supine position compared to a seated position (2). These data clearly indicate that torque production is influenced by hip position altering the stretch-tension relationship of the hamstrings and quadriceps muscle groups.

It has been well recognised that injury is most prevalent in the final stages of sports performance which coincides with the presence of muscular fatigue (3). As muscles contribute to joint stability, muscular fatigue is often suggested as a risk factor for non-contact ACL injuries (23, 32). A recent review by Ratel and Martin (24) suggest that there may be a progressive withdrawal of physiological protection against high intensity exercise induced fatigue during puberty. However, the authors are cautious as they conclude that the effects of fatigue on neuromuscular function during adolescence has scarcely been studied, despite this knowledge being able to contribute to the management of training load and recovery in maturing children (24). Data on the effects of muscle fatigue on the H/Q_{FUNC} in adults is sparse and no studies appear to have calculated the H/Q_{FUNC} using functionally relevant procedures (4). One study exploring the effects of fatigue on concentric and eccentric muscle actions suggest that eccentric torque production is more fatigue resistant than concentric torque production (26), thus the H/Q_{FUNC} should increase when fatigue is present. However, other studies on male (3, 10, 28) 3 soccer players provide a conflicting view, demonstrating a reduction in the H/Q_{FUNC} when fatigue is present, indicating compromised muscular control of the joint. Further conflicting findings are available with one study on young boys showing that eccentric and concentric elbow flexor torque production decreases

at a similar rate when fatigued (15) implying that the H/Q_{FUNC} may remain similar pre and post fatigue in children. There is currently no comparable data available on female youth, or soccer players, covering the pubertal years. Exploring the influence of fatigue on injury risk throughout puberty is important as a recent study by van der Sluis et al. (30) indicated that injuries are aligned to peak height velocity (PHV), at least in pubertal male soccer players. Whether this increased risk for injury is evident in female youth players during this period remains to be identified. To date no studies have examined the interaction between age and fatigue on H/Q_{FUNC} in female youth soccer players. As injury incidence increases throughout adolescence in female soccer players (27), the aim of this study was to explore the age related effects of soccer specific fatigue on H/Q_{FUNC} in female youth soccer players.

METHODS

Forty five females aged 12-17 years from an English FA Women's Super League Centre of Excellence were approached to participate in this study. The final sample tested was 36 (U13's [$n = 14$], U15's [$n = 9$] and U17's [$n = 13$]) as 9 participants were either injured or unavailable at the time of testing. Verbal consent was obtained from the club, followed by parental consent and player assent. Ethical approval was obtained from the institution's Research Ethics Committee. All participants completed a health questionnaire prior to testing. Participants were instructed to avoid their regular training regimens throughout the experimental period and not to take part in any vigorous physical activity 48h preceding each testing day. Age from PHV was predicted using the equation of Mirwald et al. (18). Participants visited the laboratory on two separate occasions; once for a habituation session and then for the pre/post fatigue testing. On the day of testing, participants initially performed the isokinetic tests in a non-fatigued state followed by a soccer-specific fatiguing task and then immediately re-tested.

Torque (Nm) was determined using a Biodex isokinetic dynamometer on the dominant leg. The tested range of motion was from 0° to 90° of knee flexion (0° = maximal voluntary extension). Participants were secured in a prone position on the dynamometer with the hip passively flexed at 10-20°. The axis of rotation of the lateral epicondyle was aligned with the axis of rotation of the dynamometer. The lever arm length was adjusted so that it rested on the tibia approximately 3cm above the medial malleolus. Gravity correction for limb mass was performed in accordance with the manufacturer's instructions.

Testing occurred at three angular velocities (60°/s, 120°/s and 180°/s) with concentric cycles and extension movements undertaken first, with increasing angular velocity. During the concentric measurement participants were instructed to push the lever arm up, and pull it down as hard and fast as possible, for 3 repetitions at each velocity with a 30s rest period between velocities. During the eccentric measurement participants were instructed to resist the lever arm as hard and as fast as possible. Three single maximal efforts were performed at each velocity with a 10s rest between each repetition of the same velocity and a 30s rest between movement velocities. Torque values were recorded every 10ms and the H/Q_{FUNC} calculated by expressing average eccentric hamstrings torque to average concentric quadriceps at three angles (0-10°, 11-20° and 21-30°).

The Soccer-Specific Aerobic Field Test (SAFT⁹⁰) was used to replicate the fatigue response of soccer match-play (28). The movement intensity and activity performed were maintained using verbal signals on an audio CD. The task lasted for the duration of a game the participant usually competed in, including passive rest intervals (U13 = 3 x 25min with 2min rest between periods; U15 = 2 x 40min with 10min rest between periods; U17 = 2 x 45min with 15min rest between periods). All participants were videoed during the SAFT⁹⁰ to determine group mean values for total distance covered.

The distributions of raw data sets were checked using the Kolomogorov-Smirnov test and all data had a normal distribution ($p > 0.05$). Descriptive statistics including means and standard deviations were calculated for each measure. A 3 x 3 x 3 x 2 (group x angle x velocity x time) repeated measures analysis of variance was used to explore interaction and main effects for H/Q_{FUNC}. Significant interaction or main effects were further examined using Bonferroni-corrected post hoc tests. Main effects were calculated irrespective of time, angle and velocity. The level of significance for all statistical testing was set at $P \leq 0.05$. Sample-size estimation based on the traditional method of statistical significance is not appropriate for a study designed to make an inference about real-world significance, which requires interpretation of magnitude of an outcome (13). Thus a sample of n=9 is required for within subject cross over designs based on acceptable uncertainty defined as the width of the confidence interval (13). Inferential statistics were used to examine the qualitative meaning of the observed changes in H/Q_{FUNC} from pre-to-post the soccer exercise, with data presented as the mean of the individual change and 90% confidence interval. The smallest worthwhile effect was used to determine whether the observed changes were considered negative, trivial or positive. The smallest worthwhile effect was calculated as a change in score standardised to 0.2 of the between-subject standard deviation from the pre-test condition. Probabilistic inference of each observed change being greater than the smallest worthwhile effect using the thresholds 25-75% as possibly, 75-95% as likely, 95-99.5% as very likely and >99.5% as most likely were used (13). The outcome was deemed unclear where the 90% confidence interval of the mean change overlapped both positive and negative outcomes, otherwise the outcome was clear and inference reported as the category (negative, trivial or positive) where the greatest probability was observed.

RESULTS

Participant characteristics can be seen in table 1, which indicates a significant difference between groups for all outcome variables.

Table 1: Participant characteristics by age group

| | Under 13 | Under 15 | Under 17 |
|----------------------------|-----------------|-----------------|-----------------|
| Age (y) | 12.1 ± 0.5* | 13.9 ± 0.6 | 15.8 ± 0.5 |
| Stature (m) | 1.46 ± 0.06* | 1.59 ± 0.08 | 1.66 ± 0.06 |
| Body mass (kg) | 40.8 ± 6.7* | 51.9 ± 8.8 | 61.9 ± 8.2 |
| Leg length (cm) | 68.6 ± 3.4* | 73.4 ± 3.8 | 79.8 ± 3.8 |
| Offset from PHV (y) | -0.28 ± 0.55* | 1.11 ± 0.55 | 2.93 ± 0.58 |

* Significant difference between all groups

Mean (SD) data for H/Q_{FUNC} by angle, velocity and age group, pre and post fatigue can be found in table 2.

Table 2: H/Q_{FUNC} ratio pre and post fatigue by age group, movement velocity and joint angle

| Velocity /Angle | Pre Fatigue | | | Post Fatigue | | |
|-----------------|-------------|-------------|--------------|--------------|-------------|--------------|
| | U13 | U15 | U17 | U13 | U15 | U17 |
| 0-10° | | | | | | |
| 60°/s | 1.40 ± 1.13 | 1.79 ± 1.01 | 1.42 ± 0.70* | 1.59 ± 1.61 | 0.95 ± 1.18 | 1.31 ± 0.68† |
| 120°/s | 2.01 ± 1.09 | 1.43 ± 0.92 | 1.49 ± 0.79 | 1.71 ± 1.38 | 1.27 ± 1.32 | 1.04 ± 1.02 |
| 180°/s | 1.62 ± 1.15 | 0.75 ± 0.75 | 1.08 ± 0.57 | 1.45 ± 0.92 | 0.89 ± 0.49 | 1.10 ± 1.10 |
| 10-20° | | | | | | |
| 60°/s | 1.50 ± 0.63 | 1.75 ± 0.86 | 1.30 ± | 1.69 ± 1.45 | 1.34 ± 1.24 | 2.17 ± 1.08† |
| 120°/s | 0.57* | | | 1.71 ± 1.35 | 1.43 ± 0.62 | 1.58 ± 1.04 |
| 180°/s | 1.63 ± 0.59 | 1.93 ± 0.88 | 1.90 ± 0.75 | 1.76 ± 0.88 | 1.60 ± 0.42 | 1.99 ± 1.39 |
| | 1.76 ± 0.65 | 2.09 ± 1.23 | 1.70 ± 0.57 | | | |
| 20-30° | | | | | | |
| 60°/s | 1.27 ± 0.40 | 1.35 ± 0.54 | 1.18 ± 0.26* | 1.78 ± 1.40 | 1.03 ± 0.50 | 2.30 ± 1.04† |
| 120°/s | 1.38 ± 0.45 | 1.46 ± 0.48 | 1.46 ± 0.34 | 1.36 ± 1.05 | 1.23 ± 0.37 | 1.88 ± 0.93 |
| 180°/s | 1.54 ± 0.40 | 1.52 ± 0.69 | 1.49 ± 0.30 | 1.50 ± 0.93 | 1.33 ± 0.30 | 2.07 ± 1.13 |

* Significant angle x velocity interaction effect

† Significant time x angle interaction effect

Significant interaction effects for angle x velocity ($p = 0.001$) and time x angle ($p = 0.033$) were found for the H/Q_{FUNC}. The time x angle interaction demonstrated that the ratio

decreased from pre to post fatigue at 0-10° (1.56 ± 0.94 vs 1.29 ± 1.07 [absolute change - 0.27]), remained similar at 10-20° (1.76 ± 0.74 vs 1.82 ± 1.12 [absolute change +0.06]) and increased at 20-30° (1.45 ± 0.42 vs 1.68 ± 1.02 [absolute change +0.23]). The difference in the absolute change in the H/Q_{FUNC} from pre to post fatigue between 0-10° and 20-30° was 0.50. The angle x velocity interaction demonstrated a reduction in the H/Q_{FUNC} with increasing velocity at 0-10° of flexion compared with an increase in the H/Q_{FUNC} with increasing velocity at 10-20° and 20-30° of flexion. No other significant interaction effects were observed. A significant main effect for angle ($p = 0.019$) was found with the ratio significantly higher between 10-20° than 0-10° and 20-30°. Importantly there were no main effects for time (pre fatigue 1.59 ± 0.70 vs post fatigue 1.60 ± 1.07). Although the time x group interaction effect did not reach statistical significance ($p = 0.07$) there were age related differences in the response to the soccer specific task. Relative changes and qualitative outcomes resulting from the within group analysis are presented in figure 1. The fatigue effects on the H/Q_{FUNC} were generally unclear for U13s, likely detrimental in the U15s and very likely beneficial in the U17s, across the majority of movement velocities and joint angles. The exception was for the U17s at 0-10° of knee flexion across all velocities where the findings are unclear, and the U13s at 60°/s where findings are likely beneficial.

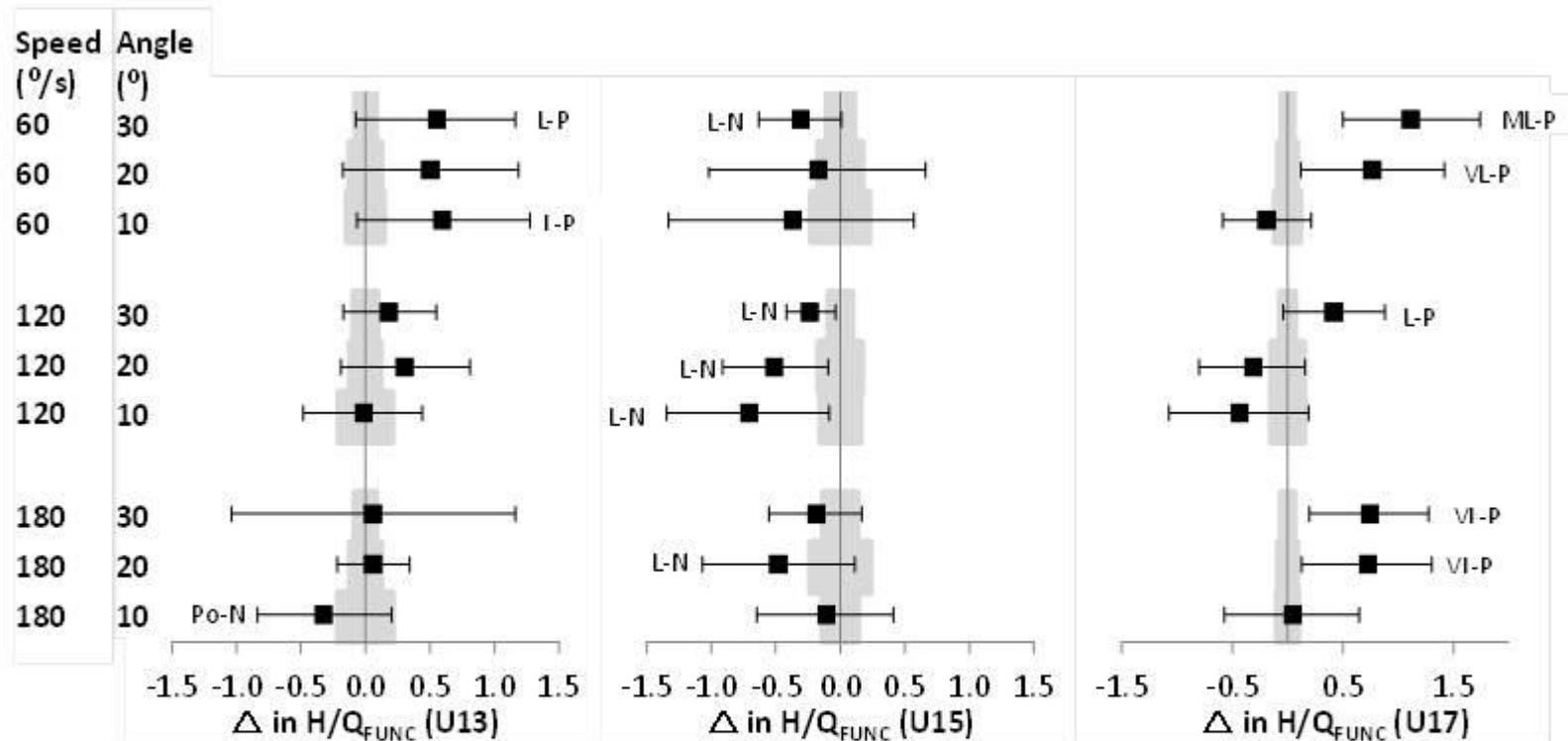


Figure 1: Mean individual change (90%CI) in U13s (left panel), U15s (middle panel) and U17s (right panel) by movement velocity and joint angle. The grey shaded area represents trivial change (smallest worthwhile effect). Inferences; Po = possibly, L = likely, VL = very likely, ML = most likely, together with N = negative, P = Positive, where no annotation is provided the inference is unclear

DISCUSSION

The major finding from this study is that altered dynamic muscular control of the knee (H/Q_{FUNC} ratio) following soccer specific fatigue is age dependent in female youth soccer players. This age related difference is reinforced by the qualitative probability data indicating that fatigue related effects in H/Q_{FUNC} were generally ‘unclear’ in the U13s, ‘likely’ detrimental in the U15s and ‘very likely’ beneficial in the U17s. This difference in the fatigue related response to dynamic muscular control clearly has practical significance and may have reached statistical significance with a larger sample size. It is difficult to relate these findings to previous research, as this is the first study to have explored the influence of soccer related fatigue on the H/Q_{FUNC} ratio in female youth soccer players using angle specific data.

The findings from the U17s in the current study show a beneficial increase in the H/Q_{FUNC} ratio when fatigue is present, a trend that is supported by previous adult data (31). Conflicting data are available showing a reduction in the H/Q_{FUNC} when fatigue is present in male adults (3), and this difference may be due to the limitations of the methods used to determine the H/Q_{FUNC} in previous studies. However, there are no comparable data in females and none in female youth soccer players. The qualitative probability data indicates that for older players there is a ‘very likely’ improvement in the H/Q_{FUNC} ratio, suggesting that post puberty muscular control is increased after soccer specific fatigue. It would appear that eccentric torque production is more resistant to fatigue than concentric torque production in post pubertal girls. The mechanisms responsible for the age related effects found in the current study might be attributed to a protective effect that is developed through maturation related changes and/or soccer training. This enhanced muscular control in the older girls may indicate that they have become quadriceps dominant and thus quadriceps torque decreased more with fatigue than hamstring torque. Previous work has demonstrated that traditional soccer training produces quadriceps dominant male youth soccer players (14). However, this

‘training’ hypothesis would require verification by exploring fatigue related effects in non-trained young girls. The age related differences might also be partly explained by maturation-related changes in muscle activation capacities. It is possible that the more mature girls have better motor unit synchronization, greater rate coding of higher threshold motor units (especially with regards to eccentric actions), and overall enhanced volitional muscle activation (7). Thus, more mature children may have a greater capacity to call upon a combination of these mechanisms, when in a fatigued state, and this may result in more effective muscular control. Age related differences in the change in the length-tension relationship, might also be partly responsible for the age related differences with more immature girls generating peak torque at relatively longer muscle lengths. It might also be that during the SAFI⁹⁰ younger players are eccentrically working closer to their peak torque and more mature players further away from their true peak (they are generating more submaximal eccentric forces at a longer muscle length). Our findings tentatively suggest that there may be development of fatigue resistance with maturational and training status that help to protect the joint. This is important, as recent research has demonstrated diminished neuromuscular control (electromechanical delay) in post pubertal girls when fatigue is present (5).

In the current study we found ‘likely’ detrimental effects of fatigue on the H/Q_{FUNC} ratio in the U15 age group and these findings are comparable to adult findings (21, 23, 28), but the mechanisms associated with the decrease in H/Q_{FUNC} at this age are difficult to ascribe. The decrease in eccentric hamstring torque following fatigue would suggest that muscular control of the joint is compromised in female soccer players around 1-year post PHV and during the advanced period of puberty. An explanation for the detrimental effects observed in the U15s may be related to the rapid change in body weight (peak weight velocity [PWV]) as disproportional increases in body fat as a percentage of body weight may mean that there is

increased ground contact loading in this age group without the concomitant increases in muscle strength from muscle growth. This hypothesis is supported by Myer et al. (19) who reported that the increased demand of pubertal changes in stature and body mass are not matched by changes in strength and neuromuscular adaptations, and may be the cause for the increase in knee abduction loads during puberty. Lower body mass and subsequent loading may also reinforce why we observed no fatigue related changes in the U13s. Additionally, there may be a protective/inhibitory mechanism in the U15 age group that does not allow them to develop large eccentric force in fatigued conditions. In very young children an inhibitory feedback control in the muscle during eccentric actions is seen as a protective mechanism during muscle lengthening (22). However, in this case the inhibitory effect is unwanted and may potentially increase injury risk.

A final explanation for why we found a negative fatigue related effect in the U15s compared with a positive effect in the U17s may be attributed to the greater relative workload completed by the U15 group compared to the U17 group (10,525m vs 10,590m) despite the fact that the U15s performed for 10min less (80 vs 90mins). Due to the focus on ecological validity it was not the purpose of this study to control for total workload but the differences in workload performed cannot be disregarded as a potential reason for the group related differences. However, in real match play situations all individuals complete different workloads, even when duration of matchplay is the same. It would appear that reduced muscular control, when fatigue is present, places the pubertal female soccer players at the greatest risk of knee injury. Our findings may start to explain the mechanisms behind the greater risk of injury in the pubertal child (27, 30). Rumpf and Cronin (27) and van der Sluis et al (30) reported that the age related increase in injury incidence is aligned with the year of PHV and that the adolescent growth spurt may lead to abnormal movement mechanics.

The 'unclear' finding in the U13 age group demonstrates that the confidence interval spans all three levels of the magnitude based inference (harmful, trivial, beneficial) and thus there is variability in this age group in relation to the response to the fatigue task. Hopkins (13) suggests that where inferences are 'unclear' that further research is required with a larger sample to resolve the uncertainty. In such instances caution should be taken in speculating on the cause of the variability in the response to the fatigue task. We might expect a wide range of maturational status in such an age group, with players experiencing different onset, magnitude, and rates of development. This in part could explain the variability in the fatigue related response, however as these were girls on an elite player pathway selection processes appears to have reduced the variability in maturation. However, this does not mean that within the U13 age group that a range of neuromuscular responses to fatigue may not be evident. Previous studies have shown that the neuromuscular response to fatigue related tasks in younger age groups is more detrimental and more variable than in older age groups (5). This suggests greater variability in muscle-tendon ability to generate and transmit force due to differences such as lower muscle activation and lower muscle fiber conduction velocity (5). There may also be greater variability in leg stiffness and less ability to recruit and utilize type II muscle fibers during maximal voluntary muscle actions. Longitudinal data that spans the maturational period may help to elucidate some of nuanced and subtle changes in fatigue related responses, especially in elite selected groups of youth athletes.

It seems that manifestations of functional change occurring with fatigue are multiple, age, joint angle, angular velocity, and action type dependent (9). We also found a significant time x joint angle interaction effect indicating that irrespective of age the H/Q_{FUNC} ratio at the most extended joint position (0-10°) was lower post-fatigue compared to pre-fatigue. As the knee moves into a more flexed position the influence of fatigue disappears and by 20-30° of knee flexion the H/Q_{FUNC} ratio increased post fatigue. These data are supported by the

qualitative probability findings indicating that despite a ‘very likely’ positive effect of fatigue on the H/Q_{FUNC} ratio in the U17s for most movement velocities and joint angles, that at all velocities the fatigue effects at 0-10° were ‘unclear’. Also where most findings were ‘unclear’ for the U13 age group at 0-10° some ‘possible negative’ changes were observed. 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 (11). The data also 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 following soccer specific fatigue, we have shown that in youth female soccer players 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 soccer as common movement patterns within the game place the knee in extended positions and females tend to land with the knee in more extended positions (12). Our data proposes that landing from a jump in the later stages of a soccer match may be a cause for increased relative risk of injury in youth female footballers due to fatigue-related alterations in muscular control. The current study is the first to demonstrate that muscular control is compromised when fatigue is present in late pubertal girls and as the joint nears full knee extension. Injury prevention programmes need to be developmentally appropriate, develop fatigue resistance and condition at the extremes of the ROM. As muscular control of the knee joint when fatigue is present is compromised around peak height velocity, when injury incidence is at it’s greatest during childhood (27), then this maturational stage should be considered an ‘at risk’ period, and targeted accordingly in terms of prevention. Well structured, strength and conditioning work should be viewed as a season-long commitment to offset the negative effects of accumulated fatigue. Rather than an additional entity to warm ups, injury prevention strategies should be embedded within training programmes for all youth athletes (20) to enhance compliance to prevention

programmes. Early intervention is critical in developing correct foundational motor control patterns and accompanying levels of muscular strength to offset the potentially harmful effects of disproportionate growth changes during puberty.

References

1. Aagaard P, Simonsen EB, Magnusson SP, Bojsen-Moller F, Dyhre-Poulsen PA. New concept for isokinetic hamstring:quadriceps muscle strength ratio. *Am J Sports Med*, 1998;26:231-237.
2. Deighan MA, Serpell BG, Bitcon MJ, De Ste Croix M.B.A. Knee joint strength ratios and effects of hip position in Rugby players. *J Stren Cond Res*, 2012;26:1959-1966.
3. Delextrat A, Gregory J, Cohen D. The Use of the Functional H:Q Ratio to Assess Fatigue in Soccer. *Int J Sports Med*, 2010;31:192-197.
4. De Ste Croix MBA, Deighan MA. Dynamic knee stability during childhood. In *Paediatric biomechanics and motor control: Theory and application* Eds (M. De Ste Croix and T. Korff), 2011; Routledge, UK
5. De Ste Croix MBA, Priestley A, Lloyd R, Oliver J. ACL injury risk in elite female youth soccer: changes in neuromuscular control of the knee following soccer fatigue *Scand J Med Sci Sports.*; 2015;25:531-8
6. De Ste Croix MBA, Deighan MA, Armstrong N. Functional eccentric-concentric ratio of knee extensors and flexors in pre-pubertal children, teenagers and adults *Int J Sports Med*, 2007;28:768-772.
7. Dotan R, Mitchell C, Cohen R, Klentrou P, Gabriel D, Falk B. Child-adult differences in muscle activation-a review. *Ped Exerc Sci*, 2012;24:2-21

8. Forbes H, Sutcliffe S, Lovell A, McNaughton LR, Polman RC, Siegler JC. Isokinetic thigh muscle ratios in youth football: Effects of age and dominance, *Int J Sports Med*, 2009;30:602-606.
9. Green HJ. Mechanisms of muscle fatigue in intense exercise. *J Sports Sci*, 1997;15:247-256.
10. Greig M. The influence of soccer-specific fatigue on peak isokinetic torque production of the knee flexors and extensors. *Am J Sports Med* 2008;36:1403-1409.
11. Griffin LY, Albohm MJ, Arendt EA. et al. Understanding and Preventing Noncontact Anterior Cruciate Ligament Injuries A Review of the Hunt Valley II Meeting, January 2005. *Amer J Sports Med*, 2006;34:1513-1532.
12. Hass C, Schick E, Tillman M, Chow J, Brunt D, Cauraugh J. Knee biomechanics during landings: Comparison of pre and post-pubescent females. *Med Sci Sports Exerc*, 2005;31:100-107
13. Hopkins W, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*, 2009;41:3-12
14. Iga J, George K, Lees A, Reilly T. Cross-sectional investigation of indices of isokinetic leg strength in youth soccer players and untrained individuals, *Scandinavian J Med Sci Sports* 2009;19:714-720.
15. Kawakami Y, Kanehisa H, Ikegawa S, Fukunaga T. Concentric and eccentric muscle strength before, during and after fatigue in 13 year-old boys, *Eur J Appl Physiol Occ Physiol*. 1993;67:121-124.
16. Kellis E, Katis A. Quantification of Functional Knee Flexor to Extensor Moment Ratio Using Isokinetics and Electromyography, *J Athl Train*, 2007;42:477-486.
17. McKay D, Broderick C, Steinbeck K. The adolescent athlete: A developmental approach to injury risk. *Ped Exerc Sci*, 2016;28:488-500

18. Mirwald R, Baxter-Jones A, Bailey D, Beunen GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc*; 2002;34:689-694
19. Myer GD, Ford KR, Divine JG, Wall EJ, Kahanov L, Hewett TE. Longitudinal assessment of noncontact anterior cruciate ligament injury risk factors during maturation in a female athlete: A case report. *J Athl Train*, 2009;44:101-109
20. Myer GD, Sugimoto D, Thomas S, Hewett TE. The Influence of Age on the Effectiveness of Neuromuscular Training to Reduce Anterior Cruciate Ligament Injury in Female Athletes: A Meta-Analysis. *Amer J Sports Med*, 2013;41:203-215
21. Oliveira AdeSC, Caputo F, Gonçalves M, Denadai BS. Heavy-intensity aerobic exercise affects the isokinetic torque and functional but not conventional hamstrings:quadriceps ratios, *J Elect Kines* 2009;19:1079-1085.
22. Oliver JL, Smith PM. Neural control of leg stiffness during hopping in boys and 21 men. *J Elect Kines*, 2010;20:973-979
23. Rahnama N, Reilly T, Lees A, Graham-Smith P. Muscle fatigue induced by exercise simulating the work rate of competitive soccer. *J Sports Sci* 2003;21:933-942
24. Ratel S, Martin V. Is There a Progressive Withdrawal of Physiological Protections against High-Intensity Exercise-Induced Fatigue during Puberty? *Sports*, 3, 346-357, 2015.
25. Renstrom P, Ljungqvist A, Arendt E. et al. Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. *Brit J Sports Med* 2008;42:394-412.
26. Roig M, O'Brien K, Kirk G. The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis, *Brit J Sports Med*, 2009;43:556-569.

27. Rumpf M, Cronin J. Injury incidence, body site, and severity in football players aged 6-18 years: implications for injury prevention. *Stren Cond J* 2012;34:20-31
28. Small K, McNaughton L, Greig M, Lovell R. The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk, *J Sci Med Sport* 2010;13:120-126.
29. Smith HC, Vacek P, Johnson RJ, Slaughterbeck JR, Hashemi J, Shultz S, Beynon BD. Risk Factors for Anterior Cruciate Ligament Injury: A Review of the Literature - Part 1: Neuromuscular and Anatomic Risk. *Sports Health: A multidisc App* 2012;1:69-78.
30. Van der Sluis A, Elferink-Gemser M, Coelho-e-Silva MJ. et al. Sport injuries aligned to peak height velocity in talented pubertal soccer players. *Int J Sports Med* 2014;35:351-355
31. Wright J, Ball N, Wood L. Fatigue, H/Q ratios and muscle coactivation in recreational football players. *Iso Exerc Sci* 2009;17:161-167.
32. Yu B, Garrett WE. Mechanisms of non-contact ACL Injuries. *Brit J Sports Med* 2007;41(Suppl 1): i47-i51.