



This is a peer-reviewed, post-print (final draft post-refereeing) version of the following in press document, This is the peer reviewed version of the following article: [FULL CITE], which has been published in final form at <http://dx.doi.org/10.1111/sms.12705>. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Self-Archiving. and is licensed under All Rights Reserved license:

Lehnert, Michal and De Ste Croix, Mark B and Zaatari, A and Hughes, Jonathan and Varekova, R and Lastovicka, O (2016) Muscular and neuromuscular control following soccer-specific exercise in male youth: Changes in injury risk mechanisms. Scandinavian Journal of Medicine and Science in Sports. ISSN 0905-7188 (In Press)

Official URL: <http://dx.doi.org/10.1111/sms.12705>
DOI: <http://dx.doi.org/10.1111/sms.12705>
EPrint URI: <http://eprints.glos.ac.uk/id/eprint/3597>

Disclaimer

The University of Gloucestershire has obtained warranties from all depositors as to their title in the material deposited and as to their right to deposit such material.

The University of Gloucestershire makes no representation or warranties of commercial utility, title, or fitness for a particular purpose or any other warranty, express or implied in respect of any material deposited.

The University of Gloucestershire makes no representation that the use of the materials will not infringe any patent, copyright, trademark or other property or proprietary rights.

The University of Gloucestershire accepts no liability for any infringement of intellectual property rights in any material deposited but will remove such material from public view pending investigation in the event of an allegation of any such infringement.

PLEASE SCROLL DOWN FOR TEXT.

This is a peer-reviewed, post-print (final draft post-refereeing) version of the following published document:

Lehnert, Michal and De Ste Croix, Mark B and Zaatar, A and Hughes, Jonathan and Varekova, R and Lastovicka, O (2016). Muscular and neuromuscular control following soccer-specific exercise in male youth: Changes in injury risk mechanisms (Online Version of Record published before inclusion in an issue). Scandinavian Journal of Medicine & Science in Sports. ISSN 09057188

Published in Scandinavian Journal of Medicine & Science in Sports, and available online at:

<http://onlinelibrary.wiley.com/doi/10.1111/sms.12705/abstract;jsessionid=6FC756510AEC6E0723D3C3438F4EDA4E.f03t04>

We recommend you cite the published (post-print) version.

The URL for the published version is <http://dx.doi.org/10.1111/sms.12705>

Disclaimer

The University of Gloucestershire has obtained warranties from all depositors as to their title in the material deposited and as to their right to deposit such material.

The University of Gloucestershire makes no representation or warranties of commercial utility, title, or fitness for a particular purpose or any other warranty, express or implied in respect of any material deposited.

The University of Gloucestershire makes no representation that the use of the materials will not infringe any patent, copyright, trademark or other property or proprietary rights.

The University of Gloucestershire accepts no liability for any infringement of intellectual property rights in any material deposited but will remove such material from public view pending investigation in the event of an allegation of any such infringement.

PLEASE SCROLL DOWN FOR TEXT.

Muscular and neuromuscular control following soccer-specific exercise in male youth: Changes in injury risk mechanisms

Michal Lehnert¹, Mark De Ste Croix², Amr Zaatar¹, Jonathan Hughes², Renata Varekova¹, Ondrej Lastovicka¹

¹Palacký University in Olomouc; Faculty of Physical Culture, Olomouc, Czech Republic

²University of Gloucestershire, Exercise and Sport Research Centre, School of Sport and Exercise, Gloucester, United Kingdom

Abstract

Poor neuromuscular control has been proposed as a risk factor for non-contact injuries, thus this study aimed to explore the effects of soccer specific fatigue on leg muscle activation, reactive strength, leg stiffness and functional hamstring/quadriceps ratio (H/Q_{FUNC}) in elite male youth soccer players. Outcome measures were determined in 18 youth players (age 14.4 ± 0.5 y; stature 169.4 ± 9.9 cm; mass 59.3 ± 8.9 kg; maturity-offset 0.86 ± 0.88 y) pre and post simulated soccer match play (SAFT⁹⁰). There was no fatigue related change in the H/Q_{FUNC} however, reactive strength and leg stiffness were both compromised ($P < 0.001$) after soccer specific fatigue. Muscle activation was also locally compromised ($P < 0.001$) in the medial hamstring and quadriceps but not in the lateral muscles. Where statistically significant changes were observed the effect sizes ranged from small to large ($0.33 - 0.97$). Compromised stiffness when fatigue is present suggests an increased yielding action, greater ground contact times, greater centre of mass displacement, and less efficient movement when the limb comes into contact with the ground. This combined with a reduction in medial quadriceps muscle activation may reflect poor kinetic chain control at the hip and an increase in knee injury risk.

Keywords: fatigue, leg stiffness, reactive strength, EMG, isokinetic.

Introduction

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 (Smith et al. 2012). There are a number of proposed mechanisms that relate to increased risk of knee and hamstring injury and numerous studies have identified that muscular and neuromuscular control are important in reducing load on the anterior cruciate ligament (ACL) (Smith et al., 2012; Renstrom et al., 2008). It has also been suggested that lower limb stiffness is an important injury protection mechanism (Alentorn-Geli et al. 2009), with low levels of stiffness associated with soft tissue injuries (Hobara et al., 2007). However, it should be noted that greater stiffness may increase the risk of bone injury (Caine et al., 2006), especially in paediatric populations where bone growth is developing. Nevertheless, few studies have explored changes in these parameters in youth athletes, especially when fatigue is present.

It is well recognised that injury is most prevalent in the final stages of sports performance which coincides with the presence of muscular fatigue (Delextrat et al., 2010). A number of studies on youth soccer players have indicated that injury incidence is greater in the last 15 minutes of each half of competitive match-play (Hawkins & Fuller, 1999; Price et al., 2004).

As muscles contribute to joint stability, muscular fatigue is often suggested as a risk factor for non-contact ACL injuries (Yu & Garrett, 2007). A deficit in muscle strength of the knee flexors and extensors and increased ipsilateral muscle strength imbalance due to neuromuscular fatigue have been associated with etiological factors of ACL injuries (Alentorn-Geli et al., 2009; Yu & Garrett, 2007). Fatigue decreases the neuromuscular component of the knee dynamic stability and the knee joint is often in positions where tendon and ligament structures are under great load, which might lead to injury of these structures (Rozzi et al., 1999). Fatigue influences neuromuscular and biomechanical factors such as muscular activation and co-activation, kinematics and kinetics, and muscle stiffness (Padua et al., 2006). It is well recognised that it is

important for muscles to produce efficient muscular control to provide compression to maintain joint stability (dynamic stability), by co-activating and producing joint stiffness and net joint moment (Aagaard et al. 2000). One of the problems with the current evidence base is that most studies examining muscular control have numerous study design flaws. For example the functional hamstring/quadriceps ratio (H/Q_{FUNC}) should be determined during the first 30° of knee flexion as this is the joint angle where injury is most likely to occur (Renstrom et al., 2008). Thus studies using a peak torque value to determine the H/Q_{FUNC} are not functionally relevant and may lead to erroneous conclusions. Only a few studies using paediatric populations have calculated the H/Q_{FUNC} at various angular positions, with all reporting an increase in the H/Q_{FUNC} as the knee approaches full extension (Kellis & Katis, 2007; De Ste Croix, 2012).

Current evidence exploring the effects of fatigue on concentric and eccentric muscle actions suggest that eccentric torque production is more fatigue resistant than concentric torque production (Roig et al., 2009), thus the H/Q_{FUNC} should increase when fatigue is present. However, a number of studies on male (Greig, 2008; Small et al., 2010) and female (Delextrat et al., 2010) soccer players have demonstrated a reduction in the H/Q_{FUNC} when fatigue is present, indicating compromised muscular control of the joint. There are very few studies that have examined the relationship between muscle control and fatigue in youth athletes. One study on female youth soccer players has indicated that the effects of soccer related fatigue on H/Q_{FUNC} is age dependent (De Ste Croix et al., 2012). The work of De Ste Croix et al. (2012) demonstrated that muscle control was compromised in early pubertal girls (U13y), unchanged in circumpubertal girls (U15y) and improved in post pubertal girls (U17y) following soccer specific fatigue. However, there appears to be no comparable data in male youth soccer.

Few studies have explored the effects of fatigue on leg stiffness in youth performers but one study on male youth players has indicated that following 42 min of soccer-specific exercise individual changes in feed-forward and reflex mediated activity of the vastus lateralis

modulated changes in Centre of Mass (CoM) displacement and leg stiffness (Oliver et al., 2014). Recently a study on female youth soccer players indicated that leg stiffness is reduced post soccer-specific exercise in U13 y-olds, but also highlighted that fatigue related changes in leg stiffness appear to be age specific (De Ste Croix et al., 2012).

Fatigue also leads to changes in reactive strength (Toumi et al., 2006) determined as the reactive strength index (RSI). RSI represents an individual ability of transition from eccentric to concentric muscle contraction (Young, 1995) and provides information on the stress exerted on the muscle-tendon complex during rebounding exercise/movements. A recent 10 year longitudinal study exploring risk factors for ACL injury indicated that low RSI was one of 8 significant predictors of ACL injury (Raschner et al., 2012). It is hypothesised that low RSI is indicative of poor stretch-shortening-cycle capability which is probably due to greater muscular latency and thus poor neuromuscular activity. However, there are very few studies dealing with RSI as a result of fatigue (Toumi, et al., 2006), moreover, these studies have never focused on youth (De Ste Croix, 2012).

Exploring the influence of fatigue on injury risk throughout puberty is important as a recent study by Van der Sluis et al. (2014) indicated that injuries are aligned to peak height velocity (PHV) and data shows a progressive rise in injury incidence based on ligament reconstruction from 12-17y-of-age (Lind et al. 2009). To date no studies have examined the interaction between neuromuscular control, reactive strength, leg stiffness, H/Q_{FUNC} and fatigue in male youth soccer players. As injury incidence increases throughout adolescence the aim of this study was to explore the effects of soccer specific fatigue on neuromuscular control, and H/Q_{FUNC} in male youth soccer players.

Material and methods

Participants

Eighteen elite young male soccer players (age 14.4 ± 0.5 y; stature 169.4 ± 9.9 cm; mass 59.3 ± 8.9 kg, maturity offset 0.86 ± 0.88 y) from a Czech club completed this study. The players trained on average four times per week, and were free of musculoskeletal lower-extremity injuries. The study was approved by the institution ethics committee and conformed to the Declaration of Helsinki regarding the use of human subjects. Written informed consent agreeing to the testing procedures and the use of the data for further research was obtained from players' parents. All tested players were fully informed about the aim of the study and the testing procedures that would be employed in the study. Leg dominance was verified (preferred kicking leg) before testing. Players completed a standardised health questionnaire prior to participation in order to be included in the research. The day before testing, the players were not exposed to any high training load. Age from PHV was predicted using the equation of Mirwald et al. (2002).

Measurements

In the first session the players underwent anthropometric testing and familiarisation with the fatigue protocol. In the second session prior to baseline testing players completed non-specific warm-up exercises, which included cycling on a stationary bicycle ergometer for 5 minutes at a self-regulated low to moderate intensity, dynamic stretching exercises which targeted the main muscle groups involved during testing, and bodyweight squats. The warm-up routine was performed under the supervision of the researcher. Testing consisted of reactive strength index (RSI), leg stiffness, isokinetic dynamometry with integrated sEMG and testing was performed in the above mentioned order. Immediately, following the fatigue protocol the tests were repeated in the same order.

Reactive strength index (RSI) was determined using an optical measurement system (Optojump-next, Microgate, Bolzano, Italy) during a drop jump test with hands on the hips. Players performed the drop jump test by stepping off a 30 cm high box with an erect standing position and upon ground contact attempted to minimise ground contact and maximise jump height (Dalleau et al., 2004). To familiarise players to the testing two trials were made followed by four measured attempts. The two best results were used for further analysis (Sole et al, 2007). RSI was calculated on the basis of the contact time on the mat and the flight time and been shown to have high test-retest reliability (Flanagan & Comyns, 2008; Flanagan et al., 2008).

To determine the stiffness of the lower limb muscles, all players performed one familiarisation set and two measured sets of 20 sub-maximal two-legged hopping using an optical measurement system (Optojump-next, Microgate, Bolzano, Italy). For all tests hands were placed on the hips and the torso was in an upright position. Frequency of hopping was assessed according to Lloyd et al. (2009) at 2.5 Hz using a mechanical metronome (GmbH & Co. KG, Isny, Germany). This frequency of jumps ensures movement patterns that reflect the typical behaviour of a spring-mass model (Lloyd et al., 2009). Of the two performed sets, the set in which the frequency of jumps better corresponded with the frequency determined by a metronome was selected. For subsequent analysis the ten consecutive jumps that were closest to the determined frequency of hopping were used (Lloyd et al., 2009). Both absolute and relative leg stiffness ($\text{kN}\cdot\text{m}^{-1}$) were calculated according to Dalleau et al. (2004) and this method has been shown to be valid and reliable in youth (Lloyd et al., 2009).

Unilateral (dominant leg) strength of the concentric action of the knee flexors and extensors was measured using an isokinetic dynamometer IsoMed 2000 (D. & R. Ferstl GmbH, Hemau, Germany). The reproducibility for the IsoMed 2000 dynamometer in measuring concentric and eccentric knee extension has been reported as being high (Dirnberger, et al., 2012). The players were tested in a sitting position with a hip angle of 100° of extension. For fixation of

the pelvis and thigh of the tested leg, fixed straps were used; shoulders were fixed by shoulder pads in the ventral-dorsal and cranial-caudal direction. The axis of rotation of the dynamometer was aligned with the lateral femoral epicondyle (axis of rotation). The arm of the dynamometer lever was fixed to the distal part of the shin with the pad placed 2.5cm over the medial apex malleolus. Individual seat settings were stored before measuring the right leg and were automatically activated in the process of measuring the left leg and follow up testing respectively. At the beginning of follow up testing individual settings were rechecked and adjusted if necessary.

Participants were instructed to hold the handgrips located at the side the seat during all testing efforts. Angular velocities of 60°/s, 180°/s and 360°/s were used for the measurement in the order from the lowest to the highest velocity. Static gravitational correction was applied according to the manufacturer's procedures. The testing range of motion was 80° and was set from 10 – 90° of knee flexion (with 0° = full voluntary extension). The testing protocol consisted of two contraction sets of concentric and two contraction sets of eccentric muscle actions. The concentric muscle action preceded the eccentric muscle action and there was a 1minute rest interval between sets. In the first warm up set the players performed five reciprocal actions (with flexion movements performed first) with a progressive rise in the muscle action until a maximum action was performed. After a 30s rest the players performed a set of six maximum repetitions. During the testing procedure the players were provided with concurrent visual feedback in the form of an isokinetic strength curve displayed on the dynamometer monitor. Absolute PT (Nm) and two joint angle-specific torque values (11–20°, 21–30°) of knee flexion and extension respectively were used for the purposes of assessment of changes in H/Q_{FUNC} ratio.

Muscle activity was recorded using surface polyelectromyography (Noraxon - Myosystem 1400A) during isokinetic muscle actions performed on the IsoMed 2000. Electrodes Kendall-

ARBO silver-silver chlorid with a solid hydrogel, oval-shaped, self-adhesive, disposable, with a diameter of 24 mm were used. The signal was captured eight manifolds with 1000 Hz frequency. Resistance poly-EMG device was $> 10 \text{ MW}$ (24 mm). Prior to application of the electrodes, the skin in that area was properly cleaned with water and dried. Surface electrodes were placed on the marked area of muscle belly in parallel with the process of muscle fibers. The distance between electrodes was 1 cm. A part of the first lead was the reference electrode located in the tibial tuberosity. For the second measurement if the electrode was dislodged during the fatigue trial then a new set of electrodes was used to reduce impedance and improve the electrode contact with the skin. Electrodes were positioned on preferential lower limb on vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF) and semitendinosus (ST) muscle. For the purpose of this study muscle activity during eccentric flexion and extension was analysed. For analysis the EMG data program was used MyoResearch XP Master Version 1.03.05. First the raw EMG data was rectified (full wave rectification) and signal smoothing applied. Second the measured values for individual muscles and velocity were divided into the resting phase and phase of muscle activity. Each of these phases was divided into three equal periods of time. Mean frequency value (Hz) was determined for each section. For normalization of electromyography signal ratio between the value of mean frequency in resting phase and the value of phase of muscle activity was used.

Fatigue protocol

The SAFT⁹⁰ was created according to data from the English Premier League (Prozone®) and was validated to replicate the fatigue response of soccer match play (Small et al., 2010). Time of fatigue protocol (2 x 35 min, 15 min half) matched regular time of competitive match of the corresponding ages category according to the current rules of Football Association of the Czech

Republic (Rule-based commission FACR, 2011). The movement intensity and activity during the test were maintained using a verbal signals from MP3 player, such as modified 15 min sequence of commands constantly changing on both ends of the track. For full details of the SAFT⁹⁰ activity profile the reader is directed towards Small et al. (2010).

Statistical analysis

Descriptive statistics (mean \pm SD) were calculated for all variables. The distributions of the data sets were checked using the Kolgomorov-Smirnov test and as most of the data did not have a normal distribution Wilcoxon Matched Pairs Tests were used to examine if soccer specific fatigue protocol led to significant changes in observed variables. The classification of effect sizes was determined by standardized pooled within sample estimate of the population standard deviation and reported as Cohen's d. The effect size is a measure of the effectiveness of a treatment and it helps to determine whether a statistically significant difference is a difference of practical concern. According to Cohen (1988), effect sizes can be classified as small ($0.00 \leq d \leq 0.49$), medium ($0.50 \leq d \leq 0.79$), and large ($d \geq 0.80$). The significance level was set at $P < 0.05$. Statistical analysis was performed using the data analysis software system Statistica, version 12 (StatSoft, Inc., Tulsa, USA).

Results

The values for measured variables pre- and post-fatigue for muscle activation are reported in Table 1. A statistically significant decrease in 7 out of 15 variables was observed, mainly in the medial thigh muscles compared to the lateral muscles. For those muscles where statistically significant changes occurred the effects sizes were small to large (range 0.33 – 0.97). Reactive strength index, absolute, and relative leg stiffness all significantly decreased ($P < 0.001$)

following soccer specific exercise (Table 2). Effect sizes were small to medium and ranged from 0.40 – 0.68. There were no statistically significant changes in the H/Q_{FUNC} irrespective of joint angle or movement velocity, and effect sizes were small (range 0 – 0.46) (Table 3).

Table 1, 2, 3 here

Discussion

The main findings of the current study indicate that simulated soccer match play significantly compromises neuromuscular control (determined as muscle activation), leg stiffness and reactive strength in youth players. Conversely muscular control (determined as the H/Q_{FUNC} ratio) was not affected. The findings also demonstrated localised fatigue related effects in neuromuscular control that might be a cause of poor kinetic chain control at the hip. The data from this study suggest that towards the end of match play youth players' ability to effectively utilise neuromuscular mechanisms to control joint movement and reduce load on ligaments is reduced and a subsequent injury risk is evident.

The effect size of the fatigue related changes in leg stiffness point to a medium effect on both absolute (ES=0.55) and relative (ES=0.68) stiffness. The reduction in leg stiffness following soccer specific exercise found in the current study has important implications as leg stiffness plays an essential role in the dynamic stability of the knee, and is governed by a number of

neurophysiological mechanisms (Lloyd et al., 2012). The findings of the current study are in agreement with one previous study on U13 female soccer players (De Ste Croix et al. 2012) and a number of adult studies (Kuitunen et al., 2002; Avela & Komi, 1998). Mechanically, a reduction in leg stiffness would typically be characterized by an increased yielding action, greater ground contact times, greater CoM displacement, and less efficient movement when the limb comes into contact with the ground (Komi, 2000). The potential consequence of such fatigue-induced reductions in ground reaction forces (and overall leg stiffness) could be an increase in shear force absorption directly by the knee joint, which would have negative permeations for ACL injury risk (Ford et al., 2010). From a neuromuscular perspective, it is likely that fatigue will have induced a change in the activation of the musculotendon unit, leading to a reduction in pre-activation prior to ground contact (feed-forward control), and an increase in co-contraction after ground contact (feedback control). Up to 97% of the variance in leg stiffness has been explained by the contribution of pre-activation and stretch-reflex response of lower limb extensor muscles (Oliver & Smith, 2010), therefore, changes in stiffness are likely to reflect changes in these control mechanisms. A reduction in leg stiffness in the measured age group may place an individual at increased risk of lower limb injury due to a reduction in dynamic stabilization of the knee. This assumption is supported to some extent by the EMG data in the current study indicating a reduction in muscle activation, especially for medial muscles within the thigh. Leg stiffness is the combination of stiffness regulation around all the joints of the lower limb and functionally represents how individuals have to control multi-joint movements during SSC exercise (Komi, 2000). Our findings therefore suggest that SSC function is reduced towards the end of simulated match play. This also has performance related implications for youth players as leg stiffness has been shown to be related to both sprint speed and jump height (Bret et al., 2002; Hennessy & Kilty, 2001). These data highlight the need for robustness and movement competency programmes to be incorporated in young male

players training as early as possible within their athletic development pathways (Myer et al., 2013).

The current study indicates that soccer specific fatigue significantly reduces muscle activation post fatigue, compromising neuromuscular control required to stabilise the joint, but only in the medial thigh muscles. The significance of this difference is also underpinned by the effect size values in case of muscle activation in measured velocities representing medium effect in the case of medial thigh muscles compared with small effects in the lateral muscles. To some extent these findings are in agreement with one previous paediatric study that demonstrated a significant increase in neuromuscular feedback mechanisms following the SAFT90 in female youth soccer players (De Ste Croix et al., 2015). This reduction in muscle activation may be due to metabolic inhibition of the contractile process and excitation-contraction coupling failure (Kent-Braun, 1999). This detrimental effect of fatigue and change in neuromuscular performance may represent an increased risk of injury. For example, research has identified that well-timed activation of the hamstring muscles can protect the ACL from mechanical strain by stabilising the tibia and reducing anterior tibial translation and that the speed of this activation is vital for the subsequent joint stability (Shultz & Perrin, 1999). However, it should be noted that voluntary muscular control forms only part of the joint stabilisation process and should be explored alongside measures of specific joint and tendon stiffness. The significant reduction in muscle activation post fatigue indicates a reduced ability of youth players to respond to a physical and visual stimulus and this might be attributed to children's more compliant muscle-tendon system which requires more time to produce a mechanical response given the same stimulus (O'Brien et al., 2010). It would appear that the reduction in muscle activation maybe largely attributed to a failure somewhere in the muscle contraction process such as deterioration in muscle conductive, contractile or elastic properties.

However, the impaired muscle activation was predominantly observed in the medial thigh

muscles (rectus femoris, vastus medialis, semitendinosus) and not in the lateral muscles (vastus lateralis, biceps femoris). This difference in the fatigue related response between the medial and lateral side may be attributed to the specific mechanics of soccer related movements, in particular cutting and change of direction. It has been evidenced that dynamic knee control is potentially compromised following fatiguing exercise with a large degree of change of direction activity (Zebis et al., 2009; Hader et al., 2014). A reduction in the EMG signal for the semitendinosus would indicate a loss of muscle coordination and therefore stability of the knee joint (Melnik et al., 2007). The loss of muscle activity impairs ACL protection in rapid change of direction actions (Zebis et al., 2011). Therefore, reduction in knee stability, via reduced semitendinosus activity, during soccer specific activities maybe a potential mechanism for loss of joint stability (Wojtys et al., 1996) and increased injury risk via greater knee valgus moments (Wikstrom et al., 2004).

Although kicking actions are not included in the SAFT⁹⁰ the localised fatigue of the medial quadriceps and hamstring might be exasperated during competitive match-play. The localised neuromuscular fatigue seen in the current study may lead to an increased risk of groin strain/rupture both in the acute setting and chronically through the season, due to the repetitive nature of the actions being undertaken. This lateral / medial difference may also indicate a potential weakness in hip extensors (glutes). For example, prospective (Nadler et al., 2000) and retrospective studies (Leetun et al., 2004; Niemuth et al., 2005) provide evidence that hip muscle weakness is associated with knee injury. Therefore, the inability to eccentrically control hip adduction and internal rotation may lead to greater dynamic lower extremity valgus that can be expected during landing, squatting, and running when fatigued from match play. Additionally, in the case of the hip, a shortened or hypertonic antagonist (e.g. Rectus femoris) may affect both the initial position of the hip joint and the extension of the hip in terms of reducing its range of motion or decreasing the activity of the muscles responsible for this

movement. This type of muscle imbalance has been referred to as the so-called “Lower cruciate syndrome” (Janda, 1982). As we did not directly measure hip abductor muscles then additional research is necessary in order to investigate the effects of fatigue on the neuromuscular response of the hip musculature during differing muscle actions.

The reduction in leg stiffness and RSI coupled with a localised reduction in muscle activation found in the current study suggests that youth players become more ‘compliant’ as they fatigue. This could contribute to the fatigue of the medial quadriceps and hamstrings from high-intensity match play and cause a higher work rate to resist the deformation of the limb during SSC activities, particularly at lower speeds where there would be greater reliance on a muscles strength capacity as opposed to its velocity capacity, following the traditional force-velocity curve concept. This reduction in stiffness and increase in compliance could lead to increased injury risk in jumping, landing and cutting manoeuvres.

Despite finding compromised leg stiffness, RSI and muscle activation in the current study we did not observe detrimental effects of muscular control, determined using the H/Q_{FUNC} ratio. The maintenance of the H/Q_{FUNC} ratio was both velocity and joint angle specific, in that in some cases concentric quadriceps and eccentric hamstring torque reduced in parallel, but in other cases torque remained unchanged. It is difficult to compare our findings to others as few studies have examined fatigue related effects on the H/Q_{FUNC} , determined close to full knee extension (where injury is most likely to occur). One previous study that has examined the H/Q_{FUNC} ratio near full knee extension pre and post the SAFT⁹⁰ in elite female youth soccer players indicated that altered dynamic muscular control of the knee was age dependent (De Ste Croix et al., 2012). In the study of De Ste Croix et al. (2012) they found no change in the H/Q_{FUNC} ratio in U13s, a significant reduction in U15s and a significant increase in U17s. The findings of the current study are in conflict with similar chronological aged female elite soccer players as we found no change in the H/Q_{FUNC} compared to the reduction observed in the U15 year-olds in the De Ste

Croix et al. (2012) study. One possible explanation for this difference might be that the boys in the current study were older than the girls in the study of De Ste Croix et al. (2012) and it is possible older children 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 (Dotan et al., 2012). Thus, older 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 younger children generating peak torque at relatively longer muscle lengths. There is also a suggestion that protective/inhibitory mechanism are important in young children 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 (Oliver & Smith, 2010). Our data does not support this hypothesis and there does not appear to be an unwanted inhibitory effect, at least not in elite post PHV male youth soccer players. Therefore, our findings tentatively support previous work that suggests that there may be development of fatigue resistance with chronological age and training status that help to protect the joint (De Ste Croix et al., 2012). This is important, especially as we have found diminished neuromuscular control in the current study when fatigue is present. It should be noted that testing in the current study was undertaken with the hip in a flexed position due to some limitations of the isokinetic dynamometer. Ideally the hip should be in a functional position that is relevant to hip positioning when injury is likely to occur (e.g. 10° of hip flexion).

Perspectives

The current study is the first to demonstrate that neuromuscular control and leg stiffness is locally compromised when fatigue is present in male youth, potentially identifying them as an 'at risk' group and therefore an emphasis of intervention programmes must be to develop neuromuscular functioning. Importantly these prevention programmes must include components that relate to hip control and fatigue resistance (Myer et al., 2013; Stastny et al., 2015). Well structured, developmentally appropriate strength and conditioning work should be viewed as a season-long commitment to offset the negative effects of accumulated fatigue. Due to the fatigue related effects observed injury prevention strategies should be related to fatigue resistance as well as movement control and isolated strengthening work for all youth athletes. Early intervention is critical in developing correct foundational motor control patterns and accompanying levels of muscular strength.

Acknowledgements

This study was supported by a research grant of Palacký University Olomouc FTK_2014003.

References

- Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Bojsen-Moller F, Dyhre-Poulsen P. Antagonist muscle coactivation during isokinetic knee extension. *Scand J Med Sci Sports* 2000; 10: 58–67.
- Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lázaro-Haro C, Cugat R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc* 2009; 17: 705–729.
- Avela J, Komi PV. Reduced stretch reflex sensitivity and muscles stiffness after long-lasting stretch-shortening cycle exercise in humans. *Eur J Appl Physiol* 1998; 78: 403–410.
- Bret C, Rahmani A, Dufour AB et al. Leg strength and stiffness as ability factors in 100 m sprint running. *J Sports Med Phys Fitness* 2002; 42: 274–281.
- Caine D, DiFiori J, Maffulli N. Physical injuries in children's and youth sports: reasons for concern? *Br J Sports Med*. 2006; 40: 749–760.

Cohen J. Statistical power analysis for the behavioral science. New Jersey, NJ: Lawrence Erlbaum Associates, Inc.; 1988.

Dalleau G, Belli A, Viale F, Lacour JR, Bourdin M. A simple method for field measurements of leg stiffness in hopping. *Int J Sports Med* 2004; 25: 170–176.

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.

De Ste Croix MBA, Priestley A, Lloyd RS, 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: 531–538.

De Ste Croix, MBA et al. Protect her knees – Exploring the role of football specific fatigue on dynamic knee stability in female youth football players. Project Report funded by the UEFA Research Grant programme; 2012.

De Ste Croix, MBA The influence of soccer match play on neuromuscular readiness to re-perform: Injury risk in elite female youth players. Project Report funded by Joao Havelange Research Scholarship (FIFA research fund); 2013.

Dirnberger J, Kösters A, Müller E. Concentric and eccentric isokinetic knee extension: A reproducibility study using the IsoMed 2000-dynamometer. *Isokin Exerc Sci* 2012; 20: 31–35.

Dotan R, Mitchell C, Cohen R, Klentrou P, Gabriel D, Falk B. Child-adult differences in muscle activation-a review. *Pediatr Excerc Sci* 2012; 24: 2–21.

Ekstrand J, Hägglund M, Waldén M. Injury incidence and injury patterns in professional football: The UEFA injury study. *Br J Sports Med*, 2009; 45: 553–558.

Flanagan EP, Comyns, TM. The use of contact time and the reactive strength index to optimize fast SSC training. *Strength Cond J* 2008; 30: 32–38.

Flanagan EP, Ebben WP, Jensen RL. Reliability of the reactive strength index and time to stabilization during depth jumps. *J Stren Condit Res* 2008; 22:1677–1682.

Ford KR, Myer GD, Hewett TE. Longitudinal effects of maturation on lower extremity joint stiffness in adolescent athletes. *Am J Sports Med* 2010; 38: 1829–1837.

Grau S, Krauss I, Maiwald C, Best R, Horstmann T. Hip abductor weakness is not the cause for iliotibial band syndrome. *Int J Sports Med* 2008; 29: 579–583.

Grau S, Krauss I, Maiwald C, Axmann D, Horstmann T, Best R. Kinematic classification of iliotibial band syndrome in runners. *Scand J Med Sci Sports* 2011; 21: 184–189.

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.

Hader K, Mendez-Villanueva A, Ahmaidi S, Williams BK, Buchheit M. Changes of direction during high-intensity intermittent runs: neuromuscular and metabolic responses. *BMC Sports Sci, Med Rehab* 2014; 6: DOI: 10.1186/2052-1847-6-2

Hawkins RD, Fuller CW. A prospective epidemiological study of injuries in four English professional football clubs. *Br J Sports Med* 1999; 33: 196–203.

Hennessy L, Kilty J. Relationship of the stretch-shortening cycle to sprint performance in trained female athletes. *J Strength Condit Res* 2001; 15: 326–331.

Hobara H, Kanosue K, Suzuki S. Changes in muscle activity with increase in leg stiffness during hopping. *Neurosci Lett* 2007; 418: 55–59.

Janda V. Fundamentals of clinics of functional (non-paretic) locomotor disorders. Brno: The Institute for Postgraduate Medical Education 1982.

Kellis E, Katis A. Quantification of functional knee flexor to extensor moment ratio using isokinetics and electromyography, *J Athl Train* 2007; 42: 477–486.

Kent-Braun JA. Central and peripheral contributions to muscle fatigue in humans during sustained maximal effort. *Eur J Appl Physiol* 1999; 80: 57–63.

Komi PV. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J Biomech* 2000; 33: 1197–1206.

Kuitunen S, Avela J, Kyröläinen H, Nicol C, Komi PV. Acute and prolonged reduction in joint stiffness in humans after exhaustive stretch-shortening cycle exercise. *Eur J Appl Physiol* 2002; 88: 107–116.

Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc* 2004; 36: 926–934.

Lind M, Menhert F, Pedersen AB. The first results from the Danish ACL reconstruction registry: epidemiologic and 2 year follow-up results from 5,818 knee ligament reconstructions. *Knee Surg Sports Traumatol Arthrosc* 2009; 17: 117–124.

Lloyd RS, Oliver JL, Hughes MG, Williams CA. Age-related differences in the neural regulation of stretch-shortening cycle activities in male youths during maximal and sub-maximal hopping. *J Electromyogr Kinesiol* 2012; 22: 37–43.

Lloyd RS, Oliver JL, Hughes MG, Williams CA. Reliability and validity of field-based measures of leg stiffness and reactive strength in youths. *J Sports Sci* 2009; 27: 1565–1573.

McCall A, Carling C, Davison M, Nedelec M, Le Gall F, Berthoin S, Dupont G. Injury risk factors, screening tests and preventative strategies: a systematic review of the evidence that underpins the perceptions and practices of 44 football (soccer) teams from various premier leagues. *Br J Sports Med* 2015; 49: 583–589.

Melnyk M, Gollhofer A. Submaximal fatigue of the hamstrings impairs specific reflex components and knee stability. *Knee Surg Sports Traumatol Arthrosc* 2007; 15: 525–532.

Mirwald R, Baxter-Jones A, Bailey D, Beunen GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc* 2002; 34: 689–694.

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. *Am J Sports Med* 2013; 41: 203–215.

Nadler SF, Malanga GA, DePrince M, Stitik TP, Feinberg JH. The relationship between lower extremity injury, low back pain, and hip muscle strength in male and female collegiate athletes. *Clin J Sport Med* 2000; 10: 89–97.

Niemuth PE, Johnson RJ, Myers MJ, Thieman TJ. Hip muscle weakness and overuse injuries in recreational runners. *Clin J Sport Med* 2005; 15: 14–21.

Oliver JL, Smith PM. Neural control of leg stiffness during hopping in boys and 21 men. *J Electromyogr Kinesiol* 2010; 20: 973–979

O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA, Maganaris CN. In vivo measurements of muscle specific tension in adults and children. *Exp Physiol* 2010; 95: 202–210.

Price RJ, Hawkins RD, Hulse MA, Hodson A. The Football Association medical research programme: an audit of injuries in academy youth football. *Br J Sports Med* 2004; 38: 466–471.

Raschner C, Platzer HP, Patterson C, Werner I, Huber R, Hildebrandt C. The relationship between ACL injuries and physical fitness in young competitive ski racers: a 10-year longitudinal study. *Br J Sports Med*. 2012; 46: 1065–1071.

Renstrom P, Ljungqvist A, Arendt E et al. Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. *Br J Sports Med* 2008; 42: 394–412.

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. *Br J Sports Med* 2009; 43: 556–569.

Rozzi SL, Lephart SM, Fu FH. Effects of muscular fatigue on knee joint laxity and neuromuscular characteristics of male and female athletes. *J Athl Train*, 1999; 34: 106–114.

Shultz S, Perrin D. Using surface electromyography to assess sex differences in neuromuscular response characteristics. *J Athl Train* 1999; 34: 165–176.

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.

Smith HC, Vacek P, Johnson RJ, Slauterbeck 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* 2012; 1: 69–78.

Sole G, Hamrén J, Milosavljevic S, Nicholson H, Sullivan SJ. Test-retest reliability of isokinetic knee extension and flexion. *Arch Phys Med Rehabil* 2007; 88: 626–631.

Stastny P, Lehnert M, Zaatari Zaki AM, Svoboda Z, Xaverova Z. Does the dumbbell-carrying position change the muscle activity in split squats and walking lunges? *J Strength Cond Res* 2015; 29: 3177–3187.

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

Wikstrom EA, Powers ME, Tillman MD. Dynamic stabilization time after isokinetic and functional fatigue. *J Athl Train*. 2004; 39: 247–253.

Wojtys EM, Wylie BB, Huston LJ. The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees. *Am J Sports Med*. 1996; 24: 615–621.

Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med* 2007; 41 (Suppl 1): 47–51.

Zebis MK, Andersen LL, Bencke J, Kjaer M, Aagaard P. Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. *Am J Sports Med*. 2009; 37: 1967–1973.

Zebis MK, Bencke J, Andersen LL, Alkjaer T, Suetta C, Mortensen P, Kjaer M, Aagaard P. Acute fatigue impairs neuromuscular activity of anterior cruciate ligament-agonist muscles in female team handball players. *Scan J Med Sci Sports*. 2011; 21: 833–840.

Table 1: Muscle activation for each muscle pre and post SAFT⁹⁰ by velocity

Velocity	Variables				
	RF	VM	VL	SEM	BF
60°/s Pre	0.47 ± 0.17*	0.50 ± 0.19*	0.56 ± 0.22	0.49 ± 0.21*	0.50 ± 0.17
Post	0.38 ± 0.10	0.44 ± 0.17	0.44 ± 0.17	0.33 ± 0.10	0.44 ± 0.23
ES	0.64	0.33	0.61	0.97	0.29
120°/s Pre	0.44 ± 0.17	0.46 ± 0.15*	0.45 ± 0.19	0.42 ± 0.15*	0.45 ± 0.33
Post	0.38 ± 0.11	0.36 ± 0.20	0.40 ± 0.19	0.33 ± 0.13	0.43 ± 0.27
ES	0.42	0.56	0.26	0.64	0.06
180°/s Pre	0.47 ± 0.29*	0.41 ± 0.28*	0.43 ± 0.28	0.44 ± 0.25	0.37 ± 0.24
Post	0.33 ± 0.09	0.27 ± 0.10	0.32 ± 0.19	0.31 ± 0.18	0.30 ± 0.18
ES	0.65	0.66	0.46	0.59	0.33

* Significant difference (P<0.05) between pre and post simulated soccer match

RF = rectus femoris; VM = vastus medialis; VL = vastus lateralis; SEM = semimembranosus;
BF = biceps femoris

Table 2: RSI, absolute and relative leg stiffness pre and post SAFT⁹⁰

Variable	PRE	POST	Effect Size
RSI	1.57 ± 0.42	1.42 ± 0.32*	0.40
Absolute leg stiffness	24.4 ± 4.7	21.7 ± 5.16*	0.55
Relative leg stiffness	34.6 ± 5.3	30.7 ± 6.1*	0.68

* Significant difference (P<0.05) between pre and post simulated soccer match

Table 3: FH/Q pre and post SAFT⁹⁰ by velocity and joint angle

Velocity	Joint Angle		
	11-20°	21-30°	Peak Torque
60°/s Pre	1.41 ± 0.38	0.88 ± 0.28	0.57 ± 0.13
Post	1.43 ± 0.63	0.98 ± 0.28	0.59 ± 0.10
ES	0.04	0.36	0.17
120°/s Pre	1.81 ± 0.95	1.16 ± 0.38	0.73 ± 0.18
Post	1.63 ± 0.74	1.11 ± 0.38	0.66 ± 0.17*
ES	0.21	0.13	0.4
180°/s Pre	3.79 ± 1.83	1.23 ± 0.44	0.81 ± 0.22
Post	4.23 ± 2.26	1.23 ± 0.50	0.72 ± 0.17
ES	0.1	0	0.46

* Significant difference (P<0.05) between pre and post simulated soccer match