Acute fatigue impairs neuromuscular activity of anterior cruciate ligament-agonist muscles in female team handball players

M. K. Zebis1,2, J. Bencke3, L. L. Andersen2, T. Alkjær4, C. Suetta1,5, P. Mortensen2, M. Kjer1, P. Aagaard1,6

1Institute of Sports Medicine Copenhagen, Bispebjerg Hospital, Copenhagen, Denmark, 2National Research Centre for the Working Environment, Copenhagen, Denmark, 3Gait Laboratory, Hvidovre University Hospital, Copenhagen, Denmark, 4Department of Neuroscience and Pharmacology, Division of Biomechanics, University of Copenhagen, Copenhagen, Denmark, 5Department of Clinical Physiology, Bispebjerg Hospital, Copenhagen, Denmark, 6Institute of Sports Sciences and Clinical Biomechanics, University of Southern Denmark, Copenhagen, Denmark

Corresponding author: M. K. Zebis, National Research Centre for the Working Environment, Lersø Parkalle` 105, DK-2100 Copenhagen Ø, Denmark. Tel: +45 39 16 53 09, Fax: +45 39 16 52 01, E-mail: mettezebis@hotmail.com

Accepted for publication 9 October 2009

In sports, like team handball, fatigue has been associated with an increased risk of anterior cruciate ligament (ACL) injury. While effects of fatigue on muscle function are commonly assessed during maximal isometric voluntary contraction (MVC), such measurements may not relate to the muscle function during match play. The purpose of this study was to investigate the effect of muscle fatigue induced by a simulated handball match on neuromuscular strategy during a functional sidecutting movement, associated with the incidence of ACL injury. Fourteen female team handball players were tested for neuromuscular activity [electromyography (EMG)] during a sidecutting maneuver on a force plate, pre and post a simulated handball match. MVC was obtained during maximal isometric quadriceps and hamstring contraction. The simulated handball match consisted of exercises mimicking handball match activity. Whereas the simulated handball match induced a decrease in MVC strength for both the quadriceps and hamstring muscles (P<0.05), a selective decrease in hamstring neuromuscular activity was seen during sidecutting (P<0.05). This study shows impaired ACL-agonist muscle (i.e. hamstring) activity during sidecutting in response to acute fatigue induced by handball match play. Thus, screening procedures should involve functional movements to reveal specific fatigue-induced deficits in ACL-agonist muscle activation during high-risk phases of match play.

In team handball – as well as in other sports involving pivoting movements – the incidence of non-contact anterior cruciate ligament (ACL) injuries has been reported to be four to eightfold higher among female athletes compared with their male counterparts (Myklebust et al., 1997). Most non-contact ACL injuries in sports and exercise occur in situations like landing, sidecutting or deceleration, which involve substantial eccentric quadriceps muscle forces (Bencke et al., 2000; Simonsen et al., 2000). During forceful quadriceps contraction, coactivation of the hamstring muscles is important to provide dynamic knee joint stabilization and to prevent excessive anterior ACL shear forces (Draganich & Vahey, 1990; More et al., 1993). Thus, the hamstring muscles are considered ACL-agonists. Different injury mechanisms for ACL injuries have been reported in the literature. The most common mechanism reported is the plant-and-cut movement with a forceful valgus at the knee joint and external or internal rotation of the tibia with the knee close to full extension (Andrews et al., 1977; Olsen et al., 2004), and dynamic valgus of the knee has been identified to predispose for ACL injury in female athletes (Hewett et al., 2005).

In sports, like team handball, it has been reported that most ACL injuries occur in the late phase of the match (Hawkins & Fuller, 1998), which suggests that fatigue may play a crucial role for the incidence of non-contact ACL injury. The effect of fatigue on neuromuscular activity have predominantly been examined during isometric muscle contraction or in isokinetic joint movements (Bigland-Ritchie et al., 1986; Rozzi et al., 1999; Kellis & Kellis, 2001; Mullany et al., 2002; Beltman et al., 2003; de Ruiter et al., 2005; Pincivero et al., 2006). However, in sports like team handball, the most representative way to examine the effect of neuromuscular fatigue on relevant movements associated with non-contact ACL injury is by evaluating the fatigue developed during match play. The sidecutting maneuver, which involves substantial eccentric quadriceps contraction, is a movement frequently associated with non-contact ACL injury (Olsen et al., 2004). Recently, strong test–retest correlations were demonstrated for the neuromuscular activity recorded during...
sidecutting, indicating that the sidecutting maneuver involves a robust and highly consistent motor program (Zebis et al., 2008).

The aim of the present study was to investigate the effect of exercise-induced muscle fatigue on ACL-agonist and -antagonist muscle coactivation in female elite handball players during a standardized sidecutting maneuver. It was hypothesized that neuromuscular activity patterns would change in response to fatigue induced by match play in a way that contribute to an elevated risk of ACL injury.

Methods

Subjects

Fourteen female handball players (age 24 ± 5 years, height 170 ± 6 cm, weight 68 ± 6 kg) volunteered to participate in the present study. All players were recruited from the same handball team in the second best national league. Players were included if they were uninjured at the time of testing and above 18 years of age. Ethical approval was obtained from the local ethics committee and informed consent was obtained from all players before testing [KF (01) 259540].

Outcome measures

Electromyography (EMG), ground reaction forces and goniometry

The skin of the subject was shaved with a hand razor and carefully cleaned with ethanol before electrode placement on the preferred push-off leg. To ensure precise and standardized placement of the electrodes at each test, the placement of the electrodes at the pre-test was drawn on the skin with a pen. Bipolar surface EMG electrodes (Medicotest M-00-S, Ølstykke, Denmark) with a 2.0 cm inter-electrode distance were placed on the medial portion of the vastus lateralis (VL), vastus medialis (VM) and rectus femoris (RF) muscles of the quadriceps femoris muscle, on the biceps femoris caput longus (Bfcl) and semitendinosus (ST) muscles of the hamstring muscle, and finally on the superficial part of the gluteus medius (GT) muscle and the muscle belly of gastrocnemius lateralis (GL) et medialis (GM).

The EMG electrodes were connected directly to small preamplifiers and the signals were lead through shielded wires to custom-built differential instrumentation amplifiers, with a bandwidth of 10–10000 Hz and a common mode rejection ratio >100 dB (Aagaard et al., 2000a, b, 2002). The preamplifiers lowered the impedance, which effectively prevented movement artifacts. Neither passive movements nor tapping the leg produced any visible EMG artifacts. It was documented previously that with this experimental setup the amount of EMG crosstalk is negligible (2–6%) (Aagaard et al., 2000a). Knee and hip joint positions were continuously measured with flexible goniometers (Penny & Giles, Christchurch, Dorset, UK), which were positioned laterally over the left knee and hip joint. Calibration of the goniometer signal was performed at anatomical knee and hip joint angles of 0° and 90° using a geometric retractor. The EMG, ground reaction forces and goniometer position signals were sampled synchronously at 1000 Hz using an external A/D-converter (dt2801-A, Data Translation, Marlboro, Massachusetts, USA) and stored in a personal computer for later analysis.

Signal treatment

All EMG signals were highpass filtered (5 Hz cut-off) and smoothed by a symmetrical moving RMS filter (30 ms time constant). Subsequently, the RMS EMG activity (mean average amplitude) were determined in predefined time intervals during the sidecutting maneuver and normalized to the peak RMS EMG amplitude recorded during the sidecutting maneuver pre and post the fatigue protocol, respectively. This procedure of EMG normalization was chosen based on recent test–retest study data obtained in our lab (Zebis et al., 2008). The software program for analyzing data was constructed so that the onset of EMG activity during sidecutting was determined by means of a mathematical algorithm procedure, which if needed could be adjusted manually. Figure 1 shows a typical example of rectified and filtered EMG signals during the sidecutting maneuver.

The term “neuromuscular activity” refers to the normalized RMS EMG amplitudes.

Maximal voluntary contraction (MVC)

MVC was performed using an isokinetic dynamometer (KinCom, Kinetic Communicator, Chattanooga Corp., Chattanooga, Tennessee, USA). The reliability and validity of the dynamometer have been described previously in detail (Farrell & Richards, 1986). Subjects were tested seated in a rigid chair with an 80° hip flexion and arms crossed. The hip and thigh were fixated by straps attached to the chair and lever arm of the dynamometer, respectively. The rotational axis of the dynamometer was aligned to the lateral femoral epicondyl, and the lower leg was attached to the dynamometer lever arm above the medial malleolus. MVC was measured at 70° knee flexion (0° = full extension). Instructions were given to the subjects to perform all contractions as fast and forceful as possible. Three trials were performed, and all trials were saved for further analysis (Aagaard et al., 2002; Andersen et al., 2005).

Sidecutting maneuver

The sidecutting maneuver is a movement that the player is able to perform in match situations when time for decision making about posture correction is extremely limited. The purpose of the sidecutting maneuver is to fake the defense player in one direction, and then move in the opposite direction. The sidecutting maneuver was performed on a force plate (Advanced Mechanical Technology Inc., Watertown, Massachusetts, USA) with simultaneous EMG recordings. Goniometry was used to measure the knee and hip joint angles continuously during the sidecutting movements. The standardized sidecutting maneuver was performed with a fixed distance of 2 m to the force plate. Instructions were given to the subjects to perform the sidecutting as fast and forceful as possible to simulate a match situation.

At each test session, five trials of sidecutting were performed by each player, and the average of these five trials was used for further examination.

Neuromuscular activity

Neuromuscular activity during sidecutting was obtained at time intervals of 10 and 50 ms before foot strike on the force plate (prelanding phase) as well as 10 and 50 ms after foot strike (landing phase). Furthermore, the knee and hip joint angles at foot strike/landing and at peak vertical ground reaction force (Fz peak) were registered by goniometers (Penny & Giles).

Ground reaction forces

The vertical (Fz) and horizontal (Fx and Fy) forces during ground contact were recorded, and the resultant horizontal
ground reaction force \((F_{xy} = \sqrt{F_x^2 + F_y^2})\) was calculated. All signals were synchronously sampled at 1000 Hz.

Fz Force

Fig. 1. Typical example of fullwave rectified electromyographic (EMG) signals (gray traces) and corresponding filtered EMG signals (black traces) obtained during a standardized sidecutting maneuver prior to the simulated handball match. The dotted line represents the defined onset of EMG. Full lines represent the ground contact phase of the sidecutting movement (landing phase).

Fatiguing protocol

On a previous occasion, heart rate was monitored from four selected players during two intensive team handball matches. The fatigue protocol was designed to resemble an intensive handball match and to mimic the recorded heart rate. The simulated handball match (30 min) consisted of a series of intermittent exercises (side-steps, cross-over steps, jumps, high- and low-intensity running and sprinting, see Table 1 and Fig. 2) mimicking handball match activity.

Perceived exertion

Ratings of perceived exertion (RPE) were recorded using the Borg 15-point category scale (Borg, 1982) immediately after cessation of the fatigue protocol.
Statistical methods

Data are presented as means ± standard deviation (SD). Differences between pre and post the fatigue protocol were evaluated using Wilcoxon’s signed-rank test for paired samples. Differences between two independent samples were evaluated using Mann–Whitney $U$-test. All tests were performed as two-tailed tests at a 5% level of significance.

Table 1. The simulated handball match

<table>
<thead>
<tr>
<th>Exercises</th>
<th>Total time (min)</th>
<th>Intervals (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Session 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treadmill running (low intensity)</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Session 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treadmill running (14 km/h with increasing inclination)</td>
<td>~5</td>
<td></td>
</tr>
<tr>
<td>Session 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side-step with cross-over cut</td>
<td>4</td>
<td>10:10</td>
</tr>
<tr>
<td>Session 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treadmill running (14 km/h with 2% inclination)</td>
<td>4</td>
<td>10:10</td>
</tr>
<tr>
<td>Session 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One-legged and two-legged jumps and sidecutting</td>
<td>4</td>
<td>10:10</td>
</tr>
<tr>
<td>Session 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treadmill running (10 km/h with 5% declination)</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Session 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMJ, one-legged jump and sidecutting</td>
<td>4</td>
<td>10:10</td>
</tr>
<tr>
<td>Session 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Side-step</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Treadmill running (to exhaustion)</td>
<td>~2</td>
<td></td>
</tr>
</tbody>
</table>

CMJ, countermovement jump.

Results

MVC

MVC strength decreased for the hamstrings and quadriceps by 16 ± 12% (from 93.6 ± 15.7 Nm to 78.9 ± 11.9 Nm, $P = 0.002$) and 22 ± 11% (from 205.4 ± 20.5 Nm to 160.3 ± 27.4 Nm, $P = 0.001$), respectively, in response to the simulated handball match. The relative decrease in MVC was not significantly different between quadriceps and hamstrings ($P = 0.160$).

Perceived exertion

Mean RPE value recorded just after cessation of the fatigue protocol was 16 ± 1 corresponding to intensities rated between “hard” and “very hard” (Fig. 3).

Knee and hip joint angles and ground reaction forces during sidecutting

The standardized sidecutting maneuver was performed in similar ways pre and post the simulated handball match, as indicated by non-significantly different knee and hip joint angles at the instant of landing, and unchanged peak vertical ground reaction force, respectively. Before the simulated handball match, the knee joint angle at landing averaged 22 ± 10° compared with 28 ± 12° after the intervention ($P = 0.131$; Table 2). Furthermore, the ground contact time during sidecutting did not change significantly after the fatigue protocol (pre: 319 ± 105 ms vs post: 299 ± 38 ms). Similarly, no change was
observed in either peak vertical ground reaction force ($F_z$ peak) during the sidecutting (pre: 1823 ± 358 N vs post: 1890 ± 461 N), or the resultant horizontal ground reaction force ($F_{xy}$ peak).

Neuromuscular activity in the prelanding phase of sidecutting

No change in neuromuscular activity was observed for any of the quadriceps muscle compartments (VL, VM and RF) at any time interval during the sidecutting maneuver. However, the fatigue protocol affected neuromuscular hamstring activity. In the 50 ms time interval before landing, neuromuscular activity decreased in biceps femoris after the fatigue protocol from 42 ± 13% to 33 ± 16% ($P < 0.05$) (Fig. 4(a)). In the 10 ms time interval before landing, neuromuscular preactivity for the biceps femoris decreased from 41 ± 13% to 31 ± 12% ($P < 0.05$), and semitendinosus activity decreased from 49 ± 14% to 40 ± 18%, ($P < 0.05$) (Fig. 4(b)). Furthermore, neuromuscular activity for the gastrocnemius lateralis decreased from 46 ± 11% to 39 ± 10% ($P < 0.05$).

Neuromuscular activity in the landing phase of sidecutting

Neuromuscular activity in the 10 ms time interval after landing decreased in the biceps femoris (39 ± 12–28 ± 12%, $P < 0.05$), and semitendinosus (46 ± 16–33 ± 16%, $P < 0.05$) (Fig. 4(c)). In contrast, no significant change was observed in neuromuscular activity during the sidecutting.
activity in the 50 ms time interval after landing for any of the examined muscles.

Table 3 Onset of EMG during sidecutting (ms before foot strike)

<table>
<thead>
<tr>
<th>Muscles</th>
<th>Pre (± SD)</th>
<th>Post (± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vastus lateralis</td>
<td>109 ± 48</td>
<td>124 ± 100</td>
</tr>
<tr>
<td>Vastus medialis</td>
<td>113 ± 48</td>
<td>103 ± 37</td>
</tr>
<tr>
<td>Rectus femoris</td>
<td>111 ± 56</td>
<td>119 ± 74</td>
</tr>
<tr>
<td>Gluteus medius</td>
<td>151 ± 39</td>
<td>151 ± 41</td>
</tr>
<tr>
<td>Biceps femoris</td>
<td>140 ± 40</td>
<td>132 ± 40</td>
</tr>
<tr>
<td>Semitendinosus</td>
<td>139 ± 39</td>
<td>139 ± 31</td>
</tr>
<tr>
<td>Gastrocnemius lateralis</td>
<td>118 ± 27</td>
<td>123 ± 30</td>
</tr>
<tr>
<td>Gastrocnemius medialis</td>
<td>130 ± 36</td>
<td>115 ± 43</td>
</tr>
</tbody>
</table>

EMG, electromyography; SD, standard deviation.

Onset of EMG activity during sidecutting

Onset of EMG activity during the sidecutting maneuver remained unchanged for all muscles examined after the simulated handball match (Table 3).

Discussion

The main finding of the present study is a selective reduction in ACL-agonist muscle (i.e. hamstring) activity during sidecutting – a movement known to be associated with ACL-injury – in response to simulated handball match play.

General muscle fatigue was observed for both the hamstring and quadriceps muscles, respectively, as evidenced by the decreased MVC. The decrease of 16–22% observed after handball match play, is less than the fatigue induced by common fatigue protocols involving isolated or maximal muscle contraction (Bigland-Ritchie et al., 1983; Ebenbichler et al., 1998; Beltman et al., 2003; de Ruiter et al., 2005). Nevertheless, the present level of fatigue resembles real-life fatigue during match play, and even submaximal hamstring fatigue has been associated with mechanical loss of knee joint stability (Melnyk & Gollhofer, 2007).

The present protocol intended to simulate a handball match with relevant movements that stressed the forces of motion in all planes. It is important to recognize that the present protocol is a compromise between true match play and standardized laboratory testing conditions. In order to standardize the fatiguing protocol as much as possible, we designed a protocol with fixed work and rest time intervals, respectively, and work intensities similar to those observed during match play as measured by the heart rate. Thus, fatigue induced by this protocol was intended to realistically mimic the effect of fatigue on sidecutting during the late phase of match play, where the risk of ACL injury is elevated (Hawkins & Fuller, 1998). The fatigue protocol was rated “hard” to “very hard” by the players, which indicates that the protocol was successful in duplicating high-intensity match play.

Surprisingly, the sidecutting maneuver was performed in a similar manner after the fatigue protocol with respect to ground contact time, ground reaction forces and hip and knee joint angles. In contrast, Augustsson et al. found that ground reaction forces as well as hip and knee joint angles decreased during the single-leg hop following a fatigue protocol consisting of consecutive unilateral knee extensions until failure (Augustsson et al., 2006). Differences in the specific fatigue protocol used and the movements evaluated make it difficult to directly compare these findings. However, the sidecutting maneuver appears to be a robust motor program learned through years of training (Zebis et al., 2008). Regardless, the skilled handball player may adjust the motor program when in a fatigued state as indicated by the present changes in neuromuscular activity.

Interestingly, even though the hamstrings and the quadriceps both were fatigued due to the simulated handball match (i.e. showed decreased MVC), neuromuscular activity was reduced selectively in the hamstring muscles during the sidecutting maneuver. The alterations in the neuromuscular pattern during sidecutting for the hamstring and gastrocnemius lateralis muscles, underlines the importance of evaluating the effect of muscle fatigue on neuromuscular activity during functional movements associated with ACL injury. The observation that EMG activity decreased in the hamstring muscles was unexpected. Fatigue during submaximal contraction conditions is normally accompanied by increased, not decreased EMG amplitude (Vitaasalo et al., 1993; Rodacki et al., 2002) due to the need of recruiting additional motor units to sustain the same load, replacing the fatigued motor units. The present reduction in hamstring EMG amplitude therefore is likely to reflect an altered motor pattern, involving diminished neuromuscular hamstring activity. Alternatively, the fatigue protocol may have led to a reduced degree of motor unit synchronization in the hamstring muscles, because reduced motor unit synchronization has been shown to decrease the amplitude of the interference surface EMG signal (Keenan et al., 2005). The selective fatigue-induced reduction in hamstring neuromuscular activity observed in the present study could potentially represent a strategy of muscle antagonist inhibition to compensate for agonist muscle fatigue (i.e. quadriceps) during sidecutting, thereby maximizing mechanical efficiency at the knee joint. If such a performance-enhancing strategy was evident in the present study, this may explain the finding of an unchanged sidecutting performance (in terms of joint angles and event
timing) between the unfatigued and fatigued state. Notably, however, the change in neuromuscular strategy induced by fatigue also represents a non-protective ACL strategy. Thus, fatigue led to a decreased hamstring neuromuscular activity, which may represent an impaired motor pattern for optimal knee joint stabilization. During explosive movements like jumping, landing, running and cutting, the lower limb muscles involved are innervated (pre-activated) before ground contact in order to build up adequate force before the impact. As ACL injuries is reported to occur during the initial phase of ground contact (Boden et al., 2000), low or reduced neuromuscular activity in the hamstring muscles reduces the potential for protecting the ACL during sidecutting. Especially, low neuromuscular activity in semitendinosus during sidecutting appears to increase the risk for sustaining an ACL injury (Zebis et al., 2009). In female athletes, non-contact rupture of the ACL typically involves a forceful valgus collapse with the knee close to full extension (Olsen et al., 2004). High semitendinosus activity during sidecutting may potentially compress the medial knee joint compartment, thereby decreasing the risk of dynamic knee joint valgus. An ACL protective strategy involving substantial neuromuscular activity of the hamstrings could be especially important for female athletes, because women produce smaller knee flexion angles along with greater valgus moments during landing and jumping than males (Malinzak et al., 2001; Ford et al., 2003, 2005; Hewett et al., 2006). The importance of an ACL protective strategy (i.e. substantial hamstring activity) is emphasized in the present study because the examined female elite handball players displayed knee joint angles at ground contact during sidecutting (22–28° from full extension) where non-contact ACL injuries are observed to occur (Boden et al., 2000; Olsen et al., 2004).

Study limitations

The present study did not use 3D kinematics analyses. Future studies should combine measurements of 3D kinematics and neuromuscular screening to examine the association between changes in neuromuscular activity and knee joint loads during high-risk movements.

In conclusion, this study shows reduced ACL-agonist muscle (i.e. hamstrings) activity during sidecutting in response to acute fatigue induced by team handball match play. Potentially, this finding implicates impaired knee joint stabilization in the fatigued state, and correspondingly increased risk of ACL injury.

Perspectives

Reduced EMG activity for semitendinosus and biceps femoris muscles in response to match-induced fatigue could potentially result in an elevated risk of ACL injury. Consequently, effective neuromuscular training regimes should be designed to counteract the fatigue-induced impairment of knee joint stability observed in female athletes by maintaining or gaining ACL protective strategies during high-risk movements.

Key words: M. semitendinosus, M. biceps femoris, Vastus lateralis, knee joint, athletes, Borg Scale.

Acknowledgements

We wish to thank Hanne Overgaard and Benny Larsson for valuable technical assistance.

Grants: This study was supported by grants from The Danish Ministry of Culture Committee for Sports Research and The Team Denmark Elite Sports Association.

References

Bigland-Ritchie B, Furbush F, Woods JJ. Fatigue of intermittent submaximal voluntary contractions: central and
Zebis et al.


