BJSM Online First, published on March 10, 2011 as 10.1136/bjsm.2010.079343

Altered muscle activation following hamstring injuries

Gisela Sole,[1] Stephan Milosavljevic,[1] Helen Nicholson,[2] S John Sullivan[1]

[1]Centre for Physiotherapy Research, University of Otago, Dunedin, New Zealand
[2]Department of Anatomy and Structural Biology, University of Otago, Dunedin, New Zealand

Correspondence to
Dr Gisela Sole, Centre of Physiotherapy Research, University of Otago, Box 56, Dunedin 9054, New Zealand; gisela.sole@otago.ac.nz

Accepted 3 February 2011

ABSTRACT

Objective The purpose of this study was to compare the electromyographic (EMG) activity of gluteal and thigh muscles of sportspeople with a recent hamstring injury with uninjured controls during a weight-bearing task.

Study design Cross-sectional.

Setting University laboratory.

Participants 16 participants with a hamstring injury (hamstring-injured group, HG) and 18 control participants (control group (CG)) participated in the study.

Main outcome measure The EMG activity of gluteal, quadriceps and hamstring muscles was recorded during a movement from double- to single-leg movement using surface electrodes.

Results The EMG onsets of biceps femoris and medial hamstrings were significantly earlier for the HG injured and the uninjured sides in preparation for single-leg standing when compared with the CG average. There were no differences in onsets for the gluteal and quadriceps muscles when comparing the injured or uninjured legs of the HG to the bilateral average of the CG.

Conclusion The earlier onset of the injured and the uninjured hamstrings in preparation for single leg stance of the HG in comparison with the CG suggests an alteration in the motor control of these muscles. Altered neuromuscular control following a hamstring injury may be a factor to be considered in the rehabilitation of hamstring injuries.

INTRODUCTION

Non-contact hamstring injuries are common in sports that include sprinting, acceleration and kicking, and have a high rate of recurrence and decreased performance levels.[1–5] Traditional rehabilitation and prevention strategies for this injury have used outcome measures that include hamstring muscle strength and flexibility.[6–9] Interestingly, recent research has suggested that exercises focusing on improving neuromuscular control around the lumbar spine and pelvis,[10] as well as sports-specific skills and enhanced balance performance, may also reduce recurrence.[11] Impaired movement discrimination during open chain movements of the lower limb have also been associated with an increased risk of hamstring injury.[12] Thus, disturbed sensory input and inhibited neuromuscular control may need to be considered in the evaluation of hamstring injuries.

Not only previous hamstring injury[4 13–17] but also knee injury, osteitis pubis[14] and calf-muscle injury[18] appear to place the sportsperson at risk of either a new or recurrent hamstring injury. Anecdotal evidence suggests that lumbar[3 19 20] and sacro-iliac disorders[21] can also predispose people to hamstring injuries. Low-back,[22] groin,[23] pelvis[24] and knee-joint[25 26] injuries have been associated with altered electromyographic (EMG) activity of lumbopelvic and lower-limb muscles. Specifically, increased hamstring activity while walking has been observed in individuals with lower-back pain (LBP)[27] and anterior cruciate ligament (ACL) deficiencies.[28] Increased hamstring activity has also been observed during an experimental task of change from double- to single-leg stance in individuals with pelvic pain,[24] and decreased activation of the gluteus maximus (GMa), and increased activation of hamstrings has been observed clinically in patients with hamstring injuries.[29]

Verrall *et al*[14] suggested that following an injury of the knee or groin, the biomechanical properties of the lower limbs may change, thereby contributing towards increased susceptibility of a future hamstring injury. We have hypothesised that changes in neuromuscular control associated with other injuries, in particular, increased hamstring muscle activation, could potentially lead to increased cumulative loading for these muscles, thereby increasing their risk for injury.[30] However, neuromuscular control as evidenced by EMG activation patterns of the agonist, synergist and antagonist pelvic and lower-limb muscles has not been investigated in sportspeople with hamstring injuries. Investigation of this potential injury mechanism may contribute towards a better understanding of neuromotor control of the hamstrings and lead to studies to determine whether exercise that focuses on neuromuscular control reduces the incidence and risk of hamstring injury.

The aim of this study was to compare the recruitment patterns of gluteal and thigh muscles during transition from double to single leg stance in participants with and without a recent hamstring injury. The secondary aim of the study is to compare the between-trial variability of EMG onsets in participants with and without a recent hamstring injury.

METHODS

Participants

Seventeen male participants clinically diagnosed as having a hamstring injury and 19 non-injured healthy male controls volunteered to participate in this study. All participants read the information sheet and signed a consent form, which was approved by the University of Otago Human Ethics Committee. Inclusion criteria for the hamstring-injured group (HG) were sportspeople who had: (1) sudden onset of non-impact posterior thigh pain during a match, competition or training within the previous 12 months; (2) an injury severe enough to have required intervention by a

health professional; (3) an injury severe enough to have caused the sportsperson to miss at least one official match, competition or at least 1 week of regular training;[15 31] and (4) returned at least partially to sports training. The inclusion criteria for the control group (CG) were (1) no known history of hamstring injury in the past that required intervention by a health professional and (2) currently participating fully in their regular sports training. Exclusion criteria for both groups were (1) knee or lumbo-pelvic injury that required health professional intervention and (2) known neurological, cardiorespiratory or systemic disorder.

EMG recordings

EMG activity was recorded bilaterally using pairs of Ag/AgCl surface electrodes (Blue Sensor disposable electrodes; Medicotest A/S, Ølstykke, Denmark), which were placed on the following muscles using Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles guidelines:[32] vastus lateralis, vastus medialis, rectus femoris, biceps femoris (BF), medial hamstrings (MH), gluteus medius and GMa, with a centre-to-centre distance of 25 mm. The ground electrode was positioned on the sternum. The skin was prepared by shaving and cleaning with alcohol swabs, and abraded firmly with a hand towel to reduce the electrical impedance to less than 10 kΩ (1% of the system's input impedance).

EMG data were collected with an eight-channel TeleMyo telemetric hardware system (Noraxon USA, Scottsdale, Arizona). The system's amplifier has a gain of 2000 and an input impedance of 10 MΩ. The analogue EMG data from the receiver were forwarded to an analogue-to-digital converter (National Instruments) and sampled at a rate of 1000 Hz using EVaRT 4.0 software (Motion Analysis, Santa Rosa, California).

Procedure

Participants stood wearing their own sport shoes with one foot on each of two Kistler force plates (BP2436 and OR6-5; Advanced Medical Technologies, Newton, Massachusetts, interfaced with the Evart 4.0 software and also sampled at 1000 Hz). They were instructed to move one leg into 90° hip and knee flexion (marching movement) as fast as possible on response to a light with either the left or right leg (indicated by a different-coloured light in a choice reaction-time task), hold the position for at least 30 s and slowly lower the foot again. The order of the sides was randomised for each trial, thus blinding the subject of the subsequent move and preventing preparation before receiving the cue. After completing seven trials from one leg, the EMG leads were connected and stabilised to the electrodes on the opposite limb and the trial repeated. The light signal was recorded and stored simultaneously with the EMG data on the EVaRT 4.0 software.

Data analysis

Data were exported to LabVIEW version 5.0, band-pass filtered between 20 and 450 Hz using a fourth-order Butterworth filter and full-wave-rectified. The onset of EMG was identified using the point at which the EMG amplitude first increased by more than three SD, for a minimum of 25 ms from the baseline level, defined as 100 ms at the commencement of the trial.

Force plate data (vertical ground force) were used to determine initiation of movement. The hip-flexion movement resulted in an anticipatory postural adjustment (APA) whereby weight was first shifted onto the moving leg before it was lifted.[33] This appeared as an increase in the vertical ground force (at T1) of that leg before the force decreased until it reached zero when the foot lifted off the force plate (T2) (figure 1). The start of the APA (T1) was determined for each trial using a Microsoft Excel graph (figure 1).[24] All muscle onsets for the hip-flexion task were expressed relative to T1, with a negative value indicating onset of activity prior to the APA and a positive value indicating onset following the APA. The time at which the foot lifted off the force plate (T2) was computed by using the LabVIEW version 5.0 program as the point at which the z-force reached zero (figure 1). The reaction time was defined as the difference between the times of the visual signal and the start of the APA (T1), and the movement time was defined as the difference between the time of the visual signal and the time at which the foot lifted off the force plate (T2).

Statistical analysis

Mean differences (95% CI) between groups were calculated for EMG onsets. Within-group differences were analysed using paired t tests, comparing injured with uninjured sides of the HG, and the CG preferred with non-preferred sides. Preliminary analysis showed no significant side-to-side differences for variables of the controls. For the between-group analyses, the variables of the preferred and non-preferred sides of the controls were thus averaged. The variables of the HG injured and the uninjured sides were compared respectively with the controls' bilateral average using independent t tests. The α level was set at 0.05.

RESULTS

Subject characteristics

Technical problems occurred with the data collection for one injured and one uninjured subject for both sides, and for the uninjured side of one HG subject. Thus, the total number of participants included in the data analysis of muscle onsets and amplitudes was 16 and 18 in the HG and CG respectively (table 1). Single electrodes had also occasionally moved during data collection, and so the number of participants included for specific muscle groups are defined in the data tables.

All participants were taking part in sports, which included rugby, soccer, hockey, netball and track athletics, at least twice weekly. In the HG, the mean time (±SD) since injury was 3.7±3.5 months (range 1–12 months), and the time before a return to partial training had been 4.3±2.1 weeks. Five of the

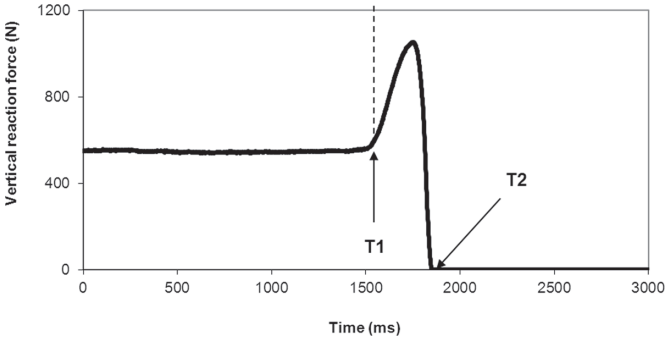

Figure 1 Vertical ground reaction force (N) of the flexing leg during one hip flexion trial. T1 indicates the time (ms) at the start of the anticipatory postural adjustment, and T2 indicates the time at which the foot is lifted off the force plate, indicating full weight-bearing on the electromyographic-monitored leg.

participants had missed up to 3 weeks of full training because of the injury, with 11 needing 4 or more weeks. Based on self-report, eight participants (50%) had incurred their hamstring injury on the preferred leg, and 12 participants (75%) had incurred the injury in the lateral hamstring muscle. The injury had been localised to the mid-thigh in 10 of the participants (62.5%), with five in the proximal part (31.3%) and one in the distal part. Five participants (31.3%) had incurred a hamstring injury in the same limb, ranging from 10 months to 3 years prior to the latest injury. Five participants had incurred a hamstring injury of the opposite limb (31.3%), ranging from 6 months to 3 years previously. Only two of the injured participants had returned to preinjury competitive and training level. Of the 14 participants that had not returned to preinjury competitive training levels, 10 indicated that they had only mild limitations with respect to strenuous sports or moderate work. The remaining two participants reported discomfort in the hamstrings during moderate work or sports activities. Three HG participants were still undergoing exercise-based rehabilitation supervised by a health professional at the time of subject recruitment.

Temporal variables

There were no significant within-group differences for the reaction and movement times, and for the muscle onsets. There were also no significant differences for reaction time when comparing the HG injured and uninjured sides with the CG bilateral average (table 2). For the movement time, the HG uninjured side was significantly faster than the CG bilateral average (p=0.049, table 2).

Onsets of all muscle groups of the CG participants were more likely to occur following the APA (T1, figure 2). There were no significant differences for the onset of the gluteal and the quadriceps muscles relative to the APA when comparing the HG injured side to the CG bilateral average and between the HG uninjured side and the CG bilateral average (figure 2, table 2). The onsets of BF and MH of the HG injured and the uninjured sides were significantly earlier than the CG bilateral average (figure 2). The CIs of the onsets of BF and MH of the HG indicate that these onsets occurred before the initiation of movement for some participants.

Table 1 Participant characteristics

Variable	Control group	Hamstring-injured group	p Value
Subjects (n)	18	16	
Age (mean±SD)	22.6±5.0	24.8±5.2	0.22
Body weight (kg (mean±SD))	80.7±12.0	79.1±8.4	0.64
Body height (cm (mean±SD))	183.0±5.1	176.9±6.5	0.01
Body mass index (mean±SD)	24.0±2.8	25.3±2.6	0.18

Coefficient of variations of temporal variables

Large mean co-efficient of variation (CVs) were found for all EMG muscle onsets, namely above 100%, with the exception of the onsets of GMa (table 2). In contrast, the reaction and movement times had low mean individual CVs, ranging between 8% and 25% (table 2). There were no significant within-group and between-group differences for all temporal CVs (table 3).

DISCUSSION

Participants with a hamstring injury had earlier onsets of the injured hamstring muscles and the contralateral side compared with controls. However, a large variability was found for EMG onsets for all participants, despite a small variability in the speed of movement.

Muscle activity prior to initiation of movement is likely to be controlled by feedforward mechanisms within the central nervous system (CNS) and serves to prepare the whole body and segmental stability for load acceptance, and maintenance of equilibrium.[34 35] This includes the first 50 to 100 ms following the initiation of movement, the minimum time required for feedback mechanisms to modify the muscle activity.[35 36] The mean onset of BF and MH of the control participants occurred more than 200 and 140 ms, respectively, following the initiation of movement. In contrast, in the HG participants, the mean onsets were less than 100 ms for the injured BF, and bilaterally for MH. The 95% CIs for these variables (figure 2) indicate that in some of the injured participants, the onsets of these muscles were prior to the start of the APA and were thus likely controlled by feedforward mechanisms. Earlier onsets were also found for the HG uninjured BF and MH in comparison with the CG bilateral average indicating that the changes in neuromuscular control are likely due to changes within the CNS, additional to peripheral changes in injured muscle.

Table 2 Between-group differences for temporal variables between the bilateral average of the control group (CG) and the injured and uninjured limbs of the hamstring-injured group (HG)

Dependent variable/ muscle group	HG injured side versus CG bilateral average	p Value	HG uninjured side vs CG bilateral average*	p Value
Time (ms)*				
Reaction time	−17 (−41 to 7)	0.154	−15 (−39 to 9)	0.217
Movement time	−39 (−90 to 12)	0.130	−54 (−108 to 0)	0.049
Electromyographic onsets relative to anticipatory postural adjustment (ms)†				
Gluteus medius	12 (−70 to 45)	0.663	−1 (−63 to 62)	0.982
Gluteus maximus	−4 (−65 to 57)	0.888	59 (−126 to 9)	0.088
Biceps femoris	−197 (−299 to −94)	<0.001	−155 (−287 to −23)	0.023
Medial hamstrings	−123 (−188 to −57)	0.001	−103 (−181 to −25)	0.011
Vastus lateralis	21 (−48 to 91)	0.529	−25 (−99 to 48)	0.477
Rectus femoris	3 (−59 to 65)	0.919	−16 (−78 to 45)	0.589
Vastus medialis	15 (−43 to 74)	0.597	−18 (−76 to 40)	0.534

*Time: negative value: HG is faster than CG.
†Muscle onsets: negative value: HG onset is earlier than CG.
Reaction time: time from visual signal to anticipatory postural adjustment; movement time: time from visual signal to foot being lifted off force platform.

The earlier onset of the hamstring muscles is similar to findings in participants with clinically diagnosed sacroiliac joint pain performing the same movement.[24] However, no difference was seen for the GMa onset relative to APA between the two groups of participants in the current study, and so this does not support previous clinical observations of delayed onset of GMa being common in patients with hamstring injuries.[29]

Despite the low individual variability of the reaction and movement time, the variability was high for the muscle onsets relative to APA, consistent with other reports of lower limb EMG onsets during functional movements.[36] The large CVs of muscle onsets of injured and asymptomatic participants of the current study and that by Van Deun *et al*[36] indicate that different strategies can be used by injured and uninjured participants to achieve the same movement.

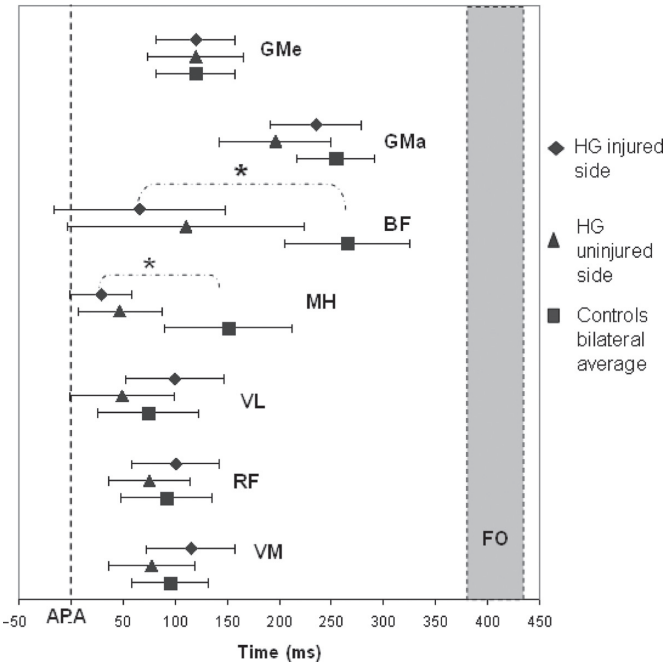

Figure 2 Mean time (95% CI) of electromyographic onsets for the stance side during transition from double- to single-leg standing of the hamstring-injured group (HG) injured and uninjured sides and the control group (CG) bilateral average. *HG injured side versus CG bilateral average and HG uninjured side versus CG bilateral average: $p<0.05$. APA, start of the anticipatory postural adjustment; BF, biceps femoris; FO, contralateral foot lifted off the force plates; GMa, gluteus maximus; GMe, gluteus medius; grey area, 95% CI of the means of time from APA to FO for combined groups; MH, medial hamstrings; RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis.

Changes in the fusimotor-spindle system have been reported with experimentally induced muscle pain.[37 38] Cameron *et al*[12] suggested that sportspeople with lower movement discrimination scores had an increased risk for incurring a hamstring injury.[12] The earlier onsets of the hamstring-injured muscles during the double- to single-leg may reflect changed proprioception[39] following an injury of the hamstring muscle. From a clinical perspective, patients with a history of hamstring injuries often complain of persistent feelings of discomfort or tightness in their hamstrings which prevent them from reattaining full preinjury training levels.[39–42] These symptoms may be present beyond the time frame normally considered to be necessary for healing of myotendinous structures. It is in these patients that changes in neurophysiological mechanisms may be evident, possibly leading to facilitation of hamstring contraction during functional movements. We suggest that this could contribute towards persistent lowered thresholds for pain or discomfort during sporting activity, such as when the athlete leans forwards while sprinting to catch a ball. Alternatively, injury of the muscle may affect the sensory input, leading to inappropriate muscle preprogramming that may place the muscle itself, or other structures of the kinetic chain, at risk of further injury.

Increased hamstring activity during walking has been observed in individuals with LBP[27] and ACL deficiencies.[28] These injuries have been associated with increased risk for incurring hamstring injuries.[3 14] We have suggested that injuries that result in loss of stability of any joint in the lower extremity and lumbopelvic area may increase the load of the hamstring muscle group.[30] Increased 'base' activation or cumulative loading of the hamstring muscles could theoretically decrease the pain- and injury-free window of movement and activity before injury thresholds are reached. Such altered activation may be a substantial contributing factor towards development of a first or recurrent hamstring injury, as well as persistence of symptoms and decreased training levels following an injury.

Table 3 Between-group comparison (two-tailed independent t tests) of coefficient of variations of the temporal variables of the injured limb of the hamstring-injured group and the bilateral average of the control group during the transition from double- to single-leg stance

Dependent variable/ muscle group	Hamstring-injured group injured side		Control group bilateral average		Mean differences (95% CI)*	p Value
	n	Mean (95% CI)	n	Mean (95% CI)		
Time (%)						
Reaction time	16	19.53 (14.93 to 24.12)	18	22.12 (17.75 to 26.50)	−2.59 (−9.19 to 4.00)	0.429
Movement time	16	8.72 (7.05 to 10.38)	18	10.19 (8.62 to 11.75)	−1.47 (−3.85 to 0.90)	0.216
Muscle onsets relative to anticipatory postural adjustment (%)						
Gastus medialis	15	174.92 (61.32 to 288.52)	17	121.75 (79.57 to 163.92)	53.17 (−67.80 to 183.15)†	0.401
Gluteus maximus	15	72.09 (−12.31 to 156.49)	18	48.52 (17.62 to 79.43)	23.57 (−63.80 to 110.94)	0.586
Biceps femoris	16	139.40 (72.55 to 206.25)	18	105.00 (61.36 to 148.65)	34.39 (−46.82 to 115.61)	0.395
Medial hamstrings	16	187.09 (105.82 to 268.37)	18	139.91 (100.29 to 179.54)	47.18 (−43.55 to 137.90)	0.297
Vastus lateralis	15	171.22 (91.65 to 250.79)	18	174.39 (94.72 to 254.06)	−3.17 (−121.354 to 115.01)	0.957
Rectus femoris	15	174.95 (16.33 to 333.56)	17	183.08 (96.61 to 269.55)	−8.13 (−190.43 to 174.16)	0.928
Vastus medialis	15	110.09 (64.05 to 156.14)	18	167.32 (89.48 to 245.15)	−57.22 (−156.29 to 41.84)	0.248

*Positive value: the hamstring-injured group variable has a larger mean CV than the control group variable.
†Equal variances not assumed.
Movement time, time from visual signal to foot being lifted off force platform; Reaction time, time from visual signal to anticipatory postural adjustment.

What is already known on this topic

- Hamstring injuries have a high recurrence risk.
- Further, groin and knee injuries have also been implicating as a risk for future hamstring injuries.
- Changes in neuromuscular control associated with other injuries, in particular, increased hamstring muscle activation, could potentially lead to increased cumulative loading for these muscles, thereby increasing their risk for injury.

What this study adds

- Changes in neuromuscular control are evident in athletes with previous hamstring injuries.
- These residual impairments may need to be considered in rehabilitative programmes.

Clinical implications

Prospective studies with professional Australian Rules football players[43] and soccer players[11] have shown that implementing sports-specific training drills and balance exercises decreased the number of hamstring injuries. Further, Sherry and Best[10] showed that rehabilitation consisting of progressive agility and trunk stabilisation exercises was more effective in preventing recurrence of hamstring injuries in comparison with a programme focusing on isolated hamstring stretching and strengthening exercises. Findings of the current study demonstrate evidence for residual impairments related to muscle activation of the injured hamstring muscles. Further comparative research investigating muscle activity of the lower limb and trunk muscles during different exercise protocols may clarify why such effects occur in the hamstrings injured. A clearer understanding of such issues may lead to more effective treatment and prevention strategies.

Methodological issues

As injury localisation was based on self-report, the diagnostic accuracy could be questioned. Although self-report of injury location has been shown to be reliable within 12 months of incurring the injury,[44] information regarding severity of the initial injury and exact diagnosis could not be confirmed. Community-level athletes, such as those participating in this study, are unlikely to have had investigative imaging to confirm the injury. Despite the absence of such investigations to define the injuries, the participants of the HG were representative of those generally assessed and treated in community clinics for hamstring injuries, as defined by the inclusion criteria.

Double- to single-leg stance was chosen as the experimental task, as the hamstrings are considered to contribute consistently towards stabilising the kinetic chain during this manoeuvre.[30] Further studies should also consider investigating muscle activity following injury during dynamic activities such as lunging, walking and running. A cross-sectional design was chosen for this research to explore whether surface EMG differentiate hamstring-injured participants from uninjured controls. This design does not allow clear inference of causality, and so this research does not provide evidence for changes in EMG muscle patterns as contributing factors towards hamstring injuries. Conclusions are limited to establishing whether there is any evidence for within- and between-group differences for the dependent variables. However, the research allowed identification of variables that could be considered for future prospective studies.

CONCLUSION

The findings of this study suggest that during the transition from double- to single-leg stance, earlier onsets of the hamstring muscles are likely to occur in participants with a previous injury of this muscle group. These differences in EMG activity may be associated with changes in lower-limb proprioception and neuromuscular control following a hamstring injury. Rehabilitative exercises of these muscles focusing on control of movement, agility and sports-specific skills could contribute towards decreasing the risk of injury recurrence.

Acknowledgements The authors thank A Gray, Department of Preventive and Social Medicine, University of Otago, for his help with the statistical analysis.

Funding New Zealand Society of Physiotherapists Scholarship Trust covered participant transport costs, running costs and a laboratory research assistant.

Competing interests None.

Ethics approval Ethics approval was provided by the University of Otago Human Ethics Committee.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES

1. **Kroll PG,** Raya MA. Hamstring muscles: an overview of anatomy, biomechanics and function, injury etiology, treatment, and prevention. *Crit Rev Phys Rehabil Med* 1997;**9**:191–203.
2. **Gabbe BJ,** Finch CF, Bennell KL, *et al.* Risk factors for hamstring injuries in community level Australian football. *Br J Sports Med* 2005;**39**:106–10.
3. **Orchard J,** Marsden J, Lord S, *et al.* Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *Am J Sports Med* 1997;**25**:81–5.
4. **Heiser TM,** Weber J, Sullivan G, *et al.* Prophylaxis and management of hamstring muscle injuries in intercollegiate football players. *Am J Sports Med* 1984;**12**:368–70.
5. **Woods C,** Hawkins RD, Maltby S, *et al.* The Football Association Medical Research Programme: an audit of injuries in professional football—analysis of hamstring injuries. *Br J Sports Med* 2004;**38**:36–41.
6. **Witvrouw E,** Danneels L, Asselman P, *et al.* Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. *Am J Sports Med* 2003;**31**:41–6.
7. **Askling C,** Saartok T, Thorstensson A. Type of acute hamstring strain affects flexibility, strength, and time to return to pre-injury level. *Br J Sports Med* 2006;**40**:40–4.
8. **O'Sullivan K,** O'Ceallaigh B, O'Connell K, *et al.* The relationship between previous hamstring injury and the concentric isokinetic knee muscle strength of Irish Gaelic footballers. *BMC Musculoskelet Disord* 2008;**9**:30.
9. **Croisier JL,** Ganteaume S, Binet J, *et al.* Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *Am J Sports Med* 2008;**36**:1469–75.
10. **Sherry MA,** Best TM. A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. *J Orthop Sports Phys Ther* 2004;**34**:116–25.
11. **Kraemer R,** Knobloch K. A soccer-specific balance training program for hamstring muscle and patellar and Achilles tendon injuries: an intervention study in premier league female soccer. *Am J Sports Med* 2009;**37**:1384–93.
12. **Cameron M,** Adams R, Maher C. Motor control and strength as predictors of hamstring injury in elite players of Australian football. *Phys Ther Sport* 2003;**4**:159–66.
13. **Ekstrand J,** Gillquist J. Soccer injuries and their mechanisms: a prospective study. *Med Sci Sports Exerc* 1983;**15**:267–70.
14. **Verrall GM,** Slavotinek JP, Barnes PG, *et al.* Clinical risk factors for hamstring muscle strain injury: a prospective study with correlation of injury by magnetic resonance imaging. *Br J Sports Med* 2001;**35**:435–9.
15. **Orchard JW.** Recurrent hamstring injury in Australian Football. *Med Sci in Sports Exerc* 1998;**30**:S52.
16. **Arnason A,** Sigurdsson SB, Gudmundsson A, *et al.* Risk factors for injuries in football. *Am J Sports Med* 2004;**32**:5S–16S.
17. **Hagel B.** Hamstring injuries in Australian football. *Clin J Sport Med* 2005;**15**:400.

18. **Orchard JW.** Intrinsic and extrinsic risk factors for muscle strains in Australian football. *Am J Sports Med* 2001;**29**:300–3.
19. **Orchard JW,** Farhart P, Leopold C. Lumbar spine region pathology and hamstring and calf injuries in athletes: is there a connection? *Br J Sports Med* 2004;**38**:502–4; discussion 502–4.
20. **Muckle DS.** Associated factors in recurrent groin and hamstring injuries. *Br J Sports Med* 1982;**16**:37–9.
21. **Cibulka MT,** Rose SJ, Delitto A, *et al.* Hamstring muscle strain treated by mobilizing the sacroiliac joint. *Phys Ther* 1986;**66**:1220–3.
22. **Hodges PW.** Lumbopelvic stability: a functional model of the biomechanics and motor control. In: Richardson C, Hodges PW, Hides C, eds. *Therapeutic Exercise for Lumbopelvic Stabilization: A Motor Control Approach for the Treatment and Prevention of Low Back Pain*. 2nd edition. Edinburgh: Churchill Livingstone 2004:13–28.
23. **Cowan SM,** Schache AG, Brukner P, *et al.* Delayed onset of transversus abdominus in long-standing groin pain. *Med Sci Sports Exerc* 2004;**36**:2040–5.
24. **Hungerford B,** Gilleard W, Hodges P. Evidence of altered lumbopelvic muscle recruitment in the presence of sacroiliac joint pain. *Spine* 2003;**28**:1593–600.
25. **Cowan SM,** Hodges PW, Bennell KL, *et al.* Altered vastii recruitment when people with patellofemoral pain syndrome complete a postural task. *Arch Phys Med Rehabil* 2002;**83**:989–95.
26. **Ageberg E.** Consequences of a ligament injury on neuromuscular function and relevance to rehabilitation—using the anterior cruciate ligament-injured knee as model. *J Electromyogr Kinesiol* 2002;**12**:205–12.
27. **Vogt L,** Pfeifer K, Banzer W. Neuromuscular control of walking with chronic low-back pain. *Man Ther* 2003;**8**:21–8.
28. **Ciccotti MG,** Kerlan RK, Perry J, *et al.* An electromyographic analysis of the knee during functional activities. II. The anterior cruciate ligament-deficient and -reconstructed profiles. *Am J Sports Med* 1994;**22**:651–8.
29. **Sahrmann SA.** *Diagnosis and Treatment of Movement Impairment Syndromes*. St Louis, MO: Mosby 2002.
30. **Sole G,** Milosavljevic S, Sullivan SJ, *et al.* Running-related hamstring injuries: a neuromuscular approach. *Phys Ther Rev* 2008;**13**:102–10.
31. **Bennell K,** Wajswelner H, Lew P, *et al.* Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. *Br J Sports Med* 1998;**32**:309–14.
32. **Hermens HJ,** Frederiks BF, Merletti R, *et al.* Seniam-European Recommendations for Surface Electromyography. Enschede: Roessingh Research and Development, 1999. http://www.seniam.org/ (accessed 17 Aug 2010).
33. **Rogers MW,** Pai YC. Dynamic transitions in stance support accompanying leg flexion movements in man. *Exp Brain Res* 1990;**81**:398–402.
34. **Andriacchi TP.** Dynamics of pathological motion: applied to the anterior cruciate deficient knee. *J Biomech* 1990;**23**(Suppl 1):99–105.
35. **Aruin AS,** Latash ML. Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. *Exp Brain Res* 1995;**103**:323–32.
36. **Van Deun S,** Staes FF, Stappaerts KH, *et al.* Relationship of chronic ankle instability to muscle activation patterns during the transition from double-leg to single-leg stance. *Am J Sports Med* 2007;**35**:274–81.
37. **Thunberg J,** Ljubisavljevic M, Djupsjöbacka M, *et al.* Effects on the fusimotor-muscle spindle system induced by intramuscular injections of hypertonic saline. *Exp Brain Res* 2002;**142**:319–26.
38. **Matre DA,** Sinkjaer T, Svensson P, *et al.* Experimental muscle pain increases the human stretch reflex. *Pain* 1998;**75**:331–9.
39. **Sutton G.** Hamstrung by hamstring strains: a review of the literature. *J Orthop Sports Phys Ther* 1984;**5**:184–95.
40. **Hoskins W,** Pollard H. The management of hamstring injury—part 1: issues in diagnosis. *Man Ther* 2005;**10**:96–107.
41. **Kujala UM,** Orava S, Järvinen M. Hamstring injuries. Current trends in treatment and prevention. *Sports Med* 1997;**23**:397–404.
42. **Drezner JA.** Practical management: hamstring muscle injuries. *Clin J Sport Med* 2003;**13**:48–52.
43. **Verrall GM,** Slavotinek JP, Barnes PG. The effect of sports specific training on reducing the incidence of hamstring injuries in professional Australian Rules football players. *Br J Sports Med* 2005;**39**:363–8.
44. **Gabbe BJ,** Finch CF, Bennell KL, *et al.* How valid is a self reported 12 month sports injury history? *Br J Sports Med* 2003;**37**:545–7.

Altered muscle activation following hamstring injuries

Gisela Sole, Stephan Milosavljevic, Helen Nicholson, et al.

Br J Sports Med published online March 10, 2011
doi: 10.1136/bjsm.2010.079343