Changes in the medial–lateral hamstring activation ratio with foot rotation during lower limb exercise

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Abstract

This paper investigated whether the ratio of medial–lateral hamstring muscular activation could be altered with changes in foot rotation position (both internal and external rotation) during three standard lower limb exercises. It has been suggested that those with medial compartment knee OA activate the lateral hamstrings more than the medial to help unload the diseased compartment; therefore, preferential activation of this muscle during lower limb exercise may help to further decrease the stresses on the articular cartilage and be an effective intervention for knee OA and lateral hamstring injury. Thirteen healthy young adult subjects were tested and average medial and lateral hamstring EMG data during the full exercise, as well as the concentric and eccentric phases, were used to calculate the medial–lateral (M–L) hamstring activation ratio for each exercise and foot position. Results suggest that internal foot rotation increases the M–L hamstring activation ratio while external foot rotation decreases this ratio. Therefore, altering the position of the foot during standard lower limb exercise can help selectively activate the medial or lateral hamstring muscle groups. This selective activation may have implication in treating symptoms of knee osteoarthritis and hamstring injury; but, longitudinal intervention studies would be needed to determine clinical utility.

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1. Introduction

Exercise is an effective tool in the treatment and prevention of musculoskeletal injury and disease. Although this is the case, more research is needed into specific forms of exercise that would be beneficial in preventing and treating certain conditions such as knee osteoarthritis (OA) (Bijlsma and Dekker, 2005).

The external adduction moment produced at the knee during gait has been implicated in the development and progression of knee osteoarthritis (Hurwitz et al., 1998; Lynn et al., 2007; Miyazaki et al., 2002; Weidenhielm et al., 1992; Schnitzer et al., 1993). For the most part, this moment is determined by a ground reaction force vector that acts medially to the knee center in the frontal plane creating a varus load on the knee, thus, increasing the stress on the knee’s medial compartment. Because of our limited ability to produce a moment in the frontal plane to counteract this external moment using muscular contractions, it is difficult to control the increased stress placed on the articular cartilage. Recently, however, it was reported that persons with medial compartment knee osteoarthritis show increased activity of the lateral hamstrings (biceps femoris) and decreased activity of the medial hamstrings (semitendinosus and semimembranosus) during gait as compared to healthy controls (Hubley-Kozey et al., 2006). This may be an attempt to unload the diseased compartment and control (in this case reduce) the external knee adduction (varus) moment by manipulating hamstring activation to produce a countereacting internal muscular knee abduction (valgus) moment. To our knowledge, the role of the
hamstrings in attenuating the frontal plane knee moments has not been investigated previously.

Since the torque produced by the medial and lateral hamstrings may play a role in attenuating the frontal plane loading (Hubley-Kooley et al., 2006), the ability of these muscles to produce torque becomes important. Due to their line of action in the frontal plane (Kendal et al., 2005), the medial and lateral hamstrings have potential to produce internal knee varus and valgus moments, respectively. However, the capacity of the medial and lateral hamstrings to generate torque may not be equal. One reason is that the moment arm of the lateral hamstrings is roughly half that of the medial hamstrings (Spoor and Vanleeuwen, 1992); therefore, given the same force production, the lateral hamstrings would produce a smaller moment. A second reason relates to the ability of the hamstring muscles to produce force. In a cadaver study (Woodley and Mercer, 2005), the physiological cross-sectional area of the medial hamstrings (semitendinosus and semimembranosus) was reported as 23.83 cm², while it was 13.04 cm² for the lateral hamstrings (biceps femoris-long and short head). Therefore, given the same activation level, the lateral hamstrings again would produce a smaller moment. It would seem that there is an inherent imbalance favoring the medial hamstrings.

This hypothesis is somewhat supported by the athletic injury literature, where the biceps femoris has been consistently identified as the most commonly injured hamstring muscle (De Smet and Best, 2000; Garrett, 1996; Koulouris and Connell, 2003; Slavotinek et al., 2002; Woods et al., 2004). Reasons given for the increased injury rate to the biceps femoris include differential innervation of the long and short heads, leading to asynchronous activation and the inability to produce the required torque to respond to external demands (Burkett, 1970). The different moment arm lengths and cross-sectional areas may also help to explain the failure to produce the required torque, something that has not been suggested in the literature.

While much of the stress on the knee’s medial compartment is due to the axial load of body, the suggested imbalance in the torque producing potential between the medial and lateral hamstrings may be another factor that explains why medial knee OA is more common in Western populations than lateral compartment disease (Felson, 1998). If the adduction moment is a risk factor for the development and progression of knee osteoarthritis, then control of this moment will be important in countering the impact of knee OA. Weaker lateral hamstrings are unable to produce a strong counter-balancing abduction moment that would help unload the medial compartment and reduce the damage that can be done by an excessive adduction moment.

Appropriate muscle function occurs when the required postural and movement tasks are performed in a well coordinated manner so that there are no negative adaptations by the musculoskeletal system (i.e. muscular injury or cartilage wear) (Schlumberger et al., 2006). One way to counteract the proposed mechanical imbalance between the medial and lateral hamstrings and avoid these negative adaptations would be to design exercises that preferentially activate the lateral hamstrings. Since the lateral hamstrings contribute to external rotation of the tibia and the medial hamstrings contribute to internal rotation of the tibia at the knee (Kendal et al., 2005), perhaps internal and external rotation of the foot during standard hamstring exercise may be able to selectively activate medial and lateral hamstrings, respectively. Electromyographic (EMG) recordings taken during isometric manual muscle testing show that the medial and lateral hamstrings can be preferentially recruited using tibial rotation (Mohamed et al., 2003); yet the relationship between foot rotation and medial/lateral hamstring muscle activation has not been investigated during standard hamstrings exercises. Therefore, the purpose of this study is to investigate the change in EMG activity of the medial and lateral hamstring with foot rotation during three standard hamstring exercises. It is hypothesized that internal rotation will favour the activation of the medial hamstrings, while external rotation will favour the lateral. Understanding the relationship between muscle activation and foot rotation may help us understand the proposed hamstring imbalance, help design injury prevention and rehabilitation exercise protocols, and discover how to redistribute the stress on the soft tissues of the knee.

2. Methods

2.1. Participants

Participants were 13 (6 M) healthy, active subjects with no history of serious lower limb trauma or surgery. The university’s Research Ethics Board approved the study and the participants provided informed consent prior to participation. The participants had a mean age of 27.7 (SD 4.0) years, with a mean height of 1.72 (SD 0.14) m and a mean body mass of 70.2 (SD 15.8) kg.

2.2. Instrumentation

A Bortec AMT-8 (Bortec Inc., Calgary, AB, Canada) 8 channel EMG system was used to collect all EMG data (differentially amplified with a gain of 1000, bandpass 10–500 Hz, CMRR = 115 dB (at 60 Hz), input impedance of 10 GΩ). Following standard skin preparation, silver–silver chloride electrodes were applied in a bi-polar configuration (3.0 cm centre-to-centre) in line with the muscles fibers over the biceps femoris (lateral hamstrings) and semimembranosus/semimembranosus (medial hamstrings) and the motor point was avoided. Also, EMG data was collected from the vastus medialis, vastus lateralis, medial gastroc, lateral gastroc, and gluteus medius muscles but only the hamstring data was analyzed in the current work. A National Instruments (National Instruments, Austin, TX, USA) 12-bit A/D card converted the EMG data from analog to digital form and a custom LabView 6.1 (National Instruments, Austin, TX, USA) program collected the EMG at 1000 Hz. Before data collection began, an EMG trace was recorded at rest. This resting muscle activity was subtracted off of the EMG signal recorded during exercise. In addition, a reference trial where subjects walked at a self-selected pace was collected. The EMG data recorded in this condition were used as reference data for nor-
malizing the magnitude of the EMG collected during the exercises.

During the exercise trials, kinematic data was collected with a Fastrak Liberty™ (Polhemus Inc., Corchester, VT, USA) electromagnetic motion tracking system. Four sensors were attached using Tufskin® spray and stretchy fabric-based adhesive tape to the lateral aspect of the foot, shank, thigh and pelvis (mid iliac crest) as far away from EMG electrodes as possible. Three dimensional position and orientation data for each sensor was collected using specialized software created for the Liberty system. Data was collected at 240 Hz. Before each exercise was collected a one second reference position trial was collected so that subsequent joint angles could be set to zero for this position.

The EMG and kinematic data were synchronized using a switch that sent a pulse to each system. The switch was turned on after both systems had begun collecting but before the subject began the exercise and was turned off after the exercise was complete. The pulse was sent, through a T connector, simultaneously to an extra channel on the breakout box that collected the EMG, and to the synch port on the Liberty system; which output a binary (on/off) channel along with position and orientation data.

2.3. Protocol

Subjects performed three hamstring exercises while EMG and kinematic data were collected: Hamstring curl (Fig. 1), Hamstring bridge (Fig. 2), One-legged deadlift (Fig. 3).

Before data collection was begun, the subject performed several practice trials and a metronome was set to their self-selected pace. The subjects then listened to the metronome while they performed each trial and were then asked to maintain that same pace. Any trial where the subject did not maintain a consistent pace was disregarded and repeated. This ensured that for any exercise all trials were performed at the same speed.

During testing, subjects performed five trials (15 total repetitions) of each exercise in the three foot rotation conditions: (1) Straight foot (STR), (2) Externally rotated foot (EXT) and (3) Internally rotated foot (INT). For the hamstring bridge and the one-legged deadlift, tape marks were made on the floor marking

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Fig. 1. Hamstring curl exercise – subject lies prone on a standard hamstring curl machine and performs a knee flexion (concentric hamstring contraction) followed by a controlled knee extension (eccentric hamstring contraction) back to the starting position. Note: CON = concentric hamstring contraction; ECC = eccentric hamstring contraction.
the position of the 2nd toe for each of the three conditions. For the hamstring curl, subjects were just asked to internally and externally rotate as much as they comfortably could. The weight used for the hamstring curl exercise was self-selected by the subject as a weight they felt they could comfortably handle for 15 repetitions. The order in which the exercises were performed was randomized, as was the order of the 15 repetitions. A convenient recovery time was allowed between repetitions.

3. Data processing

The orientation data from the Fastrak® sensors attached to each segment (pelvis, thigh, shank and foot) during the exercise trials were processed by first referencing all orientations to the static reference position trial. The floating axis method (Grood and Suntay, 1983) was then used to calculate the hip (pelvis and thigh), knee (thigh and shank) and ankle (shank and foot) angles during the exercise trials. The angle about the medial–lateral axis of the hip (Hamstring bridge and one-legged deadlift) and knee (Hamstring curl) was used to calculate the range of motion during each trial. This data was used to ensure that the exercise ROM was not different between foot rotation conditions.

Raw EMG data for the quiet resting trial, the gait reference trial and all exercise trials were full wave rectified and

Fig. 2. Hamstring bridge exercise – subject lies supine with the test leg knee at 90°, hips on the floor, and performs a posterior pelvic tilt (concentric hamstring contraction) to raise the hips up off the floor, followed by a controlled anterior pelvic tilt (eccentric hamstring contraction) to return to the starting position. Note: CON = concentric hamstring contraction; ECC = eccentric hamstring contraction.
filtered using a second order, low pass, double pass Butterworth filter with a cut-off frequency of 3 Hz. Resting muscle activity was then subtracted off of the exercise EMG data and the modified exercise EMG data was amplitude normalized using the gait trial data. This gave exercise EMG as a percent of gait activation.

Processed gait and motion data were synchronized using the switch channel. Since the EMG and kinematic data were collected at different rates, both were interpolated to 101 points (0–100% of the exercise cycle). Kinematic data were used to define the exercise cycle and split the EMG into concentric and eccentric phases for separate analyses. This was done by identifying the peak of the joint angular displacement data for each trial and then moving forward and backwards until the angular displacement dropped below 1° (cycle start and stop). Therefore, the full exercise was defined as cycle start to stop and the concentric/eccentric phases were from cycle start to peak ROM and peak ROM to cycle end, respectively. An example plot of this process is shown in Fig. 4. For each subject, foot condition and exercise, the five EMG trials were averaged to give a mean curve from which the peak EMG activity and the mean of the concentric and eccentric phases were computed.

3.1. Statistical analysis

The EMG values were extracted from the average curves for the medial and lateral hamstrings for each subject and used to calculate the medial–lateral (M/L) hamstring activation ratio. These activation ratios were then tested across the three foot rotation conditions using repeated measure ANOVAs with Bonferroni corrections to adjust the critical p-value for multiple comparisons (significance level of $p < 0.05$). If there was a main effect for foot rotation, all simple contrasts (INT–STR, EXT–STR, INT–EXT) were tested to determine the differences between individual conditions. Similar repeated measures ANOVA were conducted on the joint ROM values to ensure they were not different across conditions; and to test for differences in the M/L activation ratio across the three exercises in the straight foot position only.

4. Results

Average foot angles and joint range of motion data are shown in Table 1 for all three exercises across the three foot
rotation conditions. It should be noted that there was no effect of foot rotation on joint range of motion values for any of the three exercises.

Figs. 5–7 show the M/L hamstring activation ratios. Fig. 5 displays these values for the full curve, or entire exercise; Fig. 6 and seven display these values for the concentric and eccentric phases of the exercise, respectively. The M/L hamstring activation ratio decreased in all subjects when the foot was externally rotated and increased when the foot was internally rotated; hence, there was a main effect for foot rotation in all cases ($p < 0.05$) and all simple comparisons were significant with one exception. The eccentric phase of the one-legged deadlift exercise (Fig. 7) displayed the same trend as the other data and there was a main effect for foot rotation, but only one simple comparison (EXT–STR) was significant. This was due to the large variability between subjects especially in the internally rotated foot position.

There was also a main effect for exercise in the straight foot position ($p < 0.05$) as the M/L hamstring activation ratio was greater in the one-legged deadlift exercise than it was for the other two exercises. This activation ratio for the straight foot condition was at or slightly below 1 for the hamstring curl and hamstring bridge exercise, but was greater than 1 (indicating that the relative activation of the medial hamstrings was greater than that of the lateral hamstrings) for the one-legged deadlift exercise.

5. Discussion

The main findings of this study are: (1) Active external rotation of the foot selectively activates the lateral hamstrings and active internal rotation of the foot selectively activates the lateral hamstrings.
activates the medial hamstrings; (2) The one-legged deadlift had an increased ML hamstring activation ratio as compared to the other two exercises and was the only exercise to favour the activation of the medial hamstrings in the straight foot position and (3) The ML hamstring activation ratio during the eccentric phase of the one-legged deadlift exercise produced an unexpected result, as it was not significantly different from the normal or externally rotated positions.

During the hamstring exercises tested in this study, external rotation of the foot changed the ratio of medial–lateral muscle activation to favour the lateral hamstrings; and internal rotation changed the ratio to favour the medial hamstrings. This change in hamstring activation patterns is in accordance with previous work (Mohamed et al., 2003) and could be used to control the proposed frontal plane moment imbalances. By performing hamstring exercises with the foot in an externally rotated position, one could increase the force producing capacity of the lateral hamstrings more than the medial hamstrings, which could help overcome the smaller moment arm (Spoor and Vanleeuwen, 1992) and cross-sectional areas (Woodley and Mercer, 2005) of the lateral musculature. A change in the moment balance has implications in helping to shift the stress off of the knee’s medial compartment by producing and internal valgus moment at the knee with the hamstrings.

Although the proposed imbalance suggests that in most people the lateral hamstrings are weaker than the medial hamstrings, this may not be the case in everyone. Recent epidemiological data suggests that in Asian populations, the occurrence of lateral compartment knee OA is much more common than it is in Western populations (Felson et al., 2002). We know that in lateral compartment disease the frontal plane knee moment during gait favours the loading of the lateral compartment (Lynn et al., 2007; Weidow et al., 2006) and therefore, these patients would theoretically want to increase their internal knee adduction (varus) moment to take the stress off the diseased lateral compartment. The current data suggests that this may be accomplished by performing hamstring exercises with the foot internally rotated as this selectively activates the medial hamstrings which could potentially increase the strength of this muscle group more than the lateral hamstrings and shift the moment balance towards the medial compartment.

Another potential use for the alteration of the M/L hamstring activation ratio during lower limb exercise would be in the rehabilitation and prevention of hamstring injuries in athletic populations. Since the prevalence of injury to the lateral hamstring (biceps femoris) is much higher than the medial hamstrings in athletic populations (De Smet and Best, 2000; Garrett, 1996; Koulouris and Connell, 2003; Slavotinek et al., 2002; Woods et al., 2004), those prone to lateral hamstring injury may also benefit from performing hamstring exercise with the foot externally rotated to target the lateral hamstrings and potentially reduce the proposed medial–lateral hamstring imbalance.

The reason for this change in hamstring muscle activation ratios with foot rotation may have to do with hamstrings’ role in producing transverse plane rotations at the knee (i.e. rotation of the tibia). Along with the common function of sagittal plane flexion, the medial and lateral hamstrings can also produce internal and external rotations at the knee, respectively (Kendal et al., 2005). It may be that the subjects actively rotated their foot prior to performing an exercise and this pre-activates the musculature and increases its responsiveness to the load applied during the exercise relative to the its non pre-activated counterpart, which may have to relax to allow the tibia to rotate into position.

Foot rotation produced similar changes in the hamstring activation ratio in all exercises (increased ratio with internal rotation and decreased ratio with external rotation), but the one-legged deadlift provided some aberrant results when compared to the other two exercises. For the straight foot position, the one-legged deadlift had an increased M/L activation ratio and was the only exercise where this ratio favoured the activation of the medial hamstrings (ratio greater than 1). This may be because the one-legged deadlift is the only exercise performed in weight bearing. Under these conditions, where the joint is loaded and balancing on one leg is required, there may be a tendency to activate the stronger muscle group (medial hamstrings) to stabilize the body. If this is carried over to the single limb support phase of the gait cycle, then increased medial hamstrings activation may be counter productive to joint health. Increased activation of the medial hamstrings during single limb support would produce a varus moment at the knee which would, along with the external varus moment produced during walking (Eng and Winter, 1995), increase the stress on the cartilage of the medial compartment.

The eccentric phase of the one-legged deadlift exercise also produced the only simple comparison that did not reach significance, as the internal rotation condition was not different from the straight or external rotation conditions (Fig. 7). One reason the eccentric phase of the one-legged deadlift produced an anomalous result may be that it is the only one of the three exercises where the hamstrings are stretched beyond their resting length, as the initial phase of this exercise is an eccentric stretch of the hamstring muscles when the pelvis and trunk are rotated anteriorly during hip flexion. The other two exercises involve an initial concentric shortening of the hamstring musculature followed by an eccentric return to resting length, therefore the hamstring muscles are never stretched beyond their resting length in the hamstring bridge and hamstring curl. This initial eccentric stretch may create differing muscular reactions depending on
the hamstring flexibility of the subject. Also, the internal rotation condition was most affected as the M/L hamstring activation ratio for the one-legged deadlift exercise in the straight and the externally rotated foot positions already favoured the activation of the medial hamstrings (Fig. 7); therefore, the increased activation of the medial muscle group caused by the internal rotation of the foot, along with the stretching of that muscle beyond its resting length may cause structures like the Golgi Tendon Organ (GTO) to produce some aberrant muscular activity in those subjects with tight hamstrings. The GTO functions as a protective mechanism designed to save the muscle and its connective tissue from injury due to excessive load as they are stimulated by excessive tension in a muscle/tendon and bring about a reflex inhibition of the alpha motor neuron (McArdle et al., 1996).

It is known that exercise is an important tool in the treatment and prevention of injury and disease. For those with knee osteoarthritis, exercise has been shown to be an effective treatment strategy; although our knowledge of specific forms of exercise that may be advantageous over others is lacking (Bijlsma and Dekker, 2005). This study has demonstrated that you can selectively activate the medial and lateral hamstring muscles during standard lower limb exercise by modifying the rotation of the foot. However, it is not yet known if this could be a useful tool in treating the symptoms knee OA, slowing cartilage degradation, and in treating/preventing hamstring injury. It is possible that exercising with altered foot positions can decrease the strength imbalance of the hamstrings, and also help alter movement patterns (i.e. muscular activation strategies), allowing people to have greater control over the activation of the medial/lateral hamstrings during ambulation. The overall effect of this type of training program is difficult to predict and would require further study to determine its clinical utility. Longitudinal studies would be needed to confirm if the selective activation of the hamstring muscles during exercise could in fact be an effective intervention in the prevention and treatment of musculoskeletal injury and degenerative disease.

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References

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