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Original Research

The Relationship of Anticipatory Gluteus Medius Activity to Pelvic and Knee Stability in the Transition to Single-Leg Stance

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Abstract

Background: The knee abduction moment in a weight-bearing limb is an important risk factor of conditions such as patellofemoral pain and knee osteoarthritis. Excessive pelvic drop in single-leg stance can increase the knee abduction moment. The gluteus medius muscle is crucial to prevent pelvic drop and must be activated in anticipation of the transition from double-leg to single-leg stance.
Objective: To examine the relationship of anticipatory activity of the gluteus medius to pelvic drop and knee abduction moment.
Design: Observational, cross-sectional correlational study.
Setting: Research laboratory.
Participants: Twenty female adults (mean age 22.6 years, standard deviation 2.5) were recruited and fully participated. Participant selection was limited to healthy women who did not have a history of knee and ankle ligament injuries, any indication of knee, hip, and/or low back pain, and/or knowledge of the proper squat technique.
Methods: Participants performed 16 single-leg mini squats on their nondominant leg.
Main Outcome Measures: The onset and magnitude of anticipatory gluteus medius activity were measured in relation to toe-off of the dominant leg during the transition from double-leg to single-leg stance. Preplanned correlations between anticipatory gluteus medius onset and its activation magnitude, pelvic obliquity, and knee abduction moment were examined.
Results: The magnitude of anticipatory gluteus medius activity was significantly correlated with the knee abduction moment (r_s (18) $= -0.303$, $P < .001$) and pelvic obliquity (r_s (18) $= 0.361$, $P < .001$), whereas gluteus medius onset was not significantly correlated with either knee abduction moment or pelvic obliquity.
Conclusions: The amount of gluteus medius activity is more important for controlling knee and pelvic stability in the frontal plane than the onset of activation.

Introduction

Knee pain syndromes such as patellofemoral pain (PFP) and knee osteoarthritis (OA) are of growing importance in the health care community [1-3], especially in women, who have a higher incidence of these conditions compared with men [4,5]. These knee pain conditions have a negative impact on the overall health-related quality of life, as well as functional disability and associated health care costs [6-9]; therefore, preventing and treating these knee pain syndromes is important for improving public health and decreasing health care costs [10,11].

Internal knee abduction moments play a critical role in the development of PFP and knee OA [12,13]. Past research has found that persons with PFP exhibited a significantly greater knee abduction moment in the frontal plane during walking than did healthy persons [14]. In addition, greater knee abduction moments during walking have also been associated with the development of knee OA [15,16], and poor alignment at the knee can be considered an independent risk factor for the progression of knee OA [17].

Frontal plane pelvic motion may play an important role in changing knee abduction moments in a weight-bearing limb [12,18,19]. Pelvic rotation (frontal plane) toward or away from a support limb can change the location of the center of mass (COM) relative to the knee joint [12,19,20], thereby altering the knee abduction moment. Indeed, young adult women with PFP have been shown to experience more pelvic drop (ie, tilt of the pelvis toward the unsupporting leg) when compared with healthy persons [21]. It has also been suggested that knee OA could be accelerated by excessive pelvic drop [12]. To develop strategies for preventing excessive

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pelvic drop and subsequent increases of the knee abduction moment, previous research has focused on elucidating the role of the hip abductors in stabilizing frontal plane pelvic posture [22,23].

Because it has the largest physiological cross-sectional area among the hip abductors, the gluteus medius (GMED) mainly provides frontal plane pelvic stability [22,24,25]. Several studies have shown that persons with PFP have delayed onset of GMED activation compared with healthy persons [26-29]. Importantly, the authors of one of these studies reported that subjects with PFP showed both delayed GMED onset and increased knee abduction moment compared with healthy subjects [26], but the *relationship between* the onset of GMED and the increased knee abduction moment was not investigated. Given that an inevitable delay exists between the onset of muscle activity and force development of a muscle group [30], anticipatory activation of GMED appears crucial to control pelvic drop for the transition from single-leg to double-leg stance. It is important to elucidate how anticipatory GMED activation, in terms of onset timing and activation magnitude during a double-leg to single-leg support transition, controls frontal plane pelvic motion and the knee abduction moment. Knee disease and pain may alter the way someone moves, which then confounds the understanding of whether a change in movement caused the pain or if pain caused the change in movement; therefore, it is important to first investigate the neural control of a healthy, disease- and pain-free population to establish a normal pattern of control.

The aim of this study was to examine the relationship of anticipatory GMED activity with frontal plane pelvic motion and knee abduction moment. This correlation was measured when participants transitioned from double-leg to single-leg support while performing a single-leg mini squat. Anticipatory GMED activity was defined as activity prior to toe-off of the nonsupporting leg. We hypothesized that an earlier onset and greater magnitude of the anticipatory GMED activity of the supporting leg would be significantly correlated with decreased pelvic drop and reduced knee abduction moment of the same leg.

Methods

Participants

Participants in this study were 20 healthy women between the ages of 18 and 39 years (mean, 22.6 years; standard deviation [SD], 2.5). Because pain, injuries, and knowledge of movement mechanics may modify the movement pattern of the participants, participant selection was limited to healthy women who did not have a history of knee and ankle ligament injuries, any indication of current knee, hip, and/or low back pain, and/or knowledge of the proper squat technique. Eligibility to participate was determined through a prescreening questionnaire. This research protocol was reviewed and approved by the institutional research ethics board. Informed consent was obtained before beginning the testing protocol for all participants.

Instrumentation

Leg dominance was identified using a Modified Waterloo Footedness Questionnaire [31]. Participants rated which leg they most often used for object manipulation tasks (the dominant leg), as well as for providing support (the nondominant leg). Three-dimensional (3D) kinematic data from the pelvis and lower limbs were collected using a motion capture system (Vicon Motion Systems, Los Angeles, CA), and ground reaction forces (GRFs) were measured using force platforms under each foot (OR6; Advanced Mechanical Technology, Inc, Watertown, MA) while the participants performed single-leg mini squats (SLMS). Kinematic data and GRF data were collected at a sampling rate of 100 and 2000 Hz, respectively. An SLMS is a commonly used clinical screening tool for assessing frontal plane pelvic and knee movement during weight bearing that is functionally similar to stair negotiation [32]. Furthermore, the quality of SLMS performance can reliably represent the functional quality of GMED activation [33]. To perform the SLMS, participants first transitioned from double-leg to single-leg standing, and then lowered their body by flexing their hip, knee, and ankle (Figure 1). Surface electromyography (EMG; 2400GT2, Noraxon Inc, Scottsdale, AZ), sampled at 2000 Hz, was used to record the muscle activity of the GMED [34,35] during the movement.

Testing Protocol

An initial 60-second quiet standing trial was collected to obtain baseline EMG values. Participants then performed a total of 32 SLMS. Movement speed was standardized using the beat of a metronome set at 80 beats per minute: At the first beat, the participant lifted her toe off the force platform to make the transition from

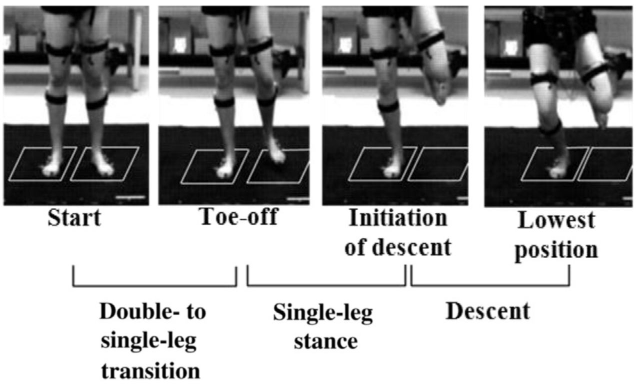

Figure 1. Sequential movement events.

double- to single-leg stance. At the next beat she descended her body to the lowest position of the SLMS. Naturally, each participant needed time to stabilize herself on one leg before initiating the descent. Such time between toe-off and initiation of descent was defined as the single-leg stance phase. As a result, the SLMS was broken down into 3 phases (Figure 1): (1) double-leg stance, (2) single-leg stance, and (3) descent. Participants were instructed to keep their arms crossed on their chest for the entire movement. Sixteen SLMS were performed on each leg, with the order of the supporting leg randomized but limited to a maximum of 4 in a row on the same leg. The participants were given instructions for the SLMS and allowed to practice the movement at least 5 times for familiarization before starting. If the participant needed more than 10 practices, at least 1 minute of rest was given after the 10 practices to prevent fatigue. She was also allowed to rest between trials to prevent fatigue.

Data Analysis

The analysis in this study focused on the transition from double-leg to single-leg stance to investigate anticipatory GMED control. The descent of the SLMS was not included in the analysis because it is well established that GMED activation is more involved in transverse rotation of the hip rather than frontal plane rotation of the pelvis when the hip is flexed [23,36]. All analyses focused on the nondominant leg because this leg is more likely than the dominant leg to be involved in stability-related tasks during daily activities [31,37].

Kinematic and kinetic data were processed using a 4th order Butterworth digital filter, Visual 3D (C-Motion, Inc, Kingston, Ontario, Canada) and custom MATLAB (R2006b for PC; MathWorks, Natick, MA) routines. The 3D marker trajectories and GRF data were low-pass filtered at a cutoff frequency of 8 Hz and 250 Hz, respectively.

Toe-off was identified using GRFs. Toe-off was defined as the point when the vertical force dropped below a threshold value defined as 2 SDs of the zero load force tracing. This toe-off timing defined the end of the double-leg stance and the start of the single-leg stance. A virtual pelvic center marker midway between the bilateral anterior superior iliac spine and posterior superior iliac spine was used for detecting when a participant initiated the descent phase. Descent start was defined as the first point when the vertical velocity of the pelvic center marker became negative.

The hip and knee joint center were identified using the functional calibration data according to the method described by Schwartz and Rozumalski [38]. Standard 3D rigid body analyses were performed for the lower limb, with anatomic axes defined using joint centers [39] and segmental kinematics tracked with 4 marker rigid clusters on each segment.

The frontal plane angle of the pelvis was defined by the vertical axis of the laboratory and the line connecting the hip joint center and midway between the left anterior superior iliac spine and posterior superior iliac spine. To quantify the pelvic obliquity occurring during single-leg stance, the net change of pelvic angle between toe-off and initiation of descent was calculated. An increase in the pelvic angle represented pelvic obliquity, whereas a decrease in the angle represented pelvic drop.

Inverse dynamics were used to calculate the net resultant internal knee abduction moment. The principle moments of inertia, the segment masses, and the locations of the COM of each segment were obtained from anthropometric tables [40]. The joint moment was normalized to participants' weight and height. The net change of the knee abduction moment during single-leg stance was included in the data analysis.

EMG data was high-pass filtered at 10 Hz, fully rectified, and then low-pass filtered at 50 Hz [41]. The electromechanical delay between the GMED onset and the generation of force during an SLMS has not previously been reported; therefore, the GMED activity integrated over 60 msec prior to toe-off was chosen as a measure of anticipatory activation based on studies of other activities, including comfortable walking [42,43]. These EMG magnitudes were normalized to the EMG integrated over $\pm$ 30 msec around the largest peak burst of EMG throughout all trials [44]. GMED onset was calculated using a threshold of 1.5 times the mean amplitude value of the quiet standing trial. EMG amplitudes were required to exceed the threshold for a minimum of 65 msec.

Statistical Analysis

Data were analyzed using SPSS versions 19.0 and 22 (IBM Corp, Armonk, NY) with an α level set at 0.05. Normal distribution of the data was tested using the Shapiro-Wilk test, skewness, and kurtosis analyses. The mean of the normally distributed data and the median of the non-normal data were used as the representative samples. Correlation statistics were used to examine if the GMED activation timing and magnitude on the supporting leg were significantly related to the pelvic obliquity and knee abduction moment of the same leg. In addition, the relationship between pelvic obliquity and knee abduction moment was examined to confirm if pelvic motion contributes to the change of knee abduction moment. Spearman's rho (two-tailed) was used to determine the correlation coefficients to better fit the nonlinear relationship between the variables [45].

Results

All 20 participants showed onset of the GMED before toe-off of the nonsupporting leg (Figure 2). Table 1 shows the mean and SD of the outcome variables. The GMED onset occurred on average 330 $\pm$ 133 msec before

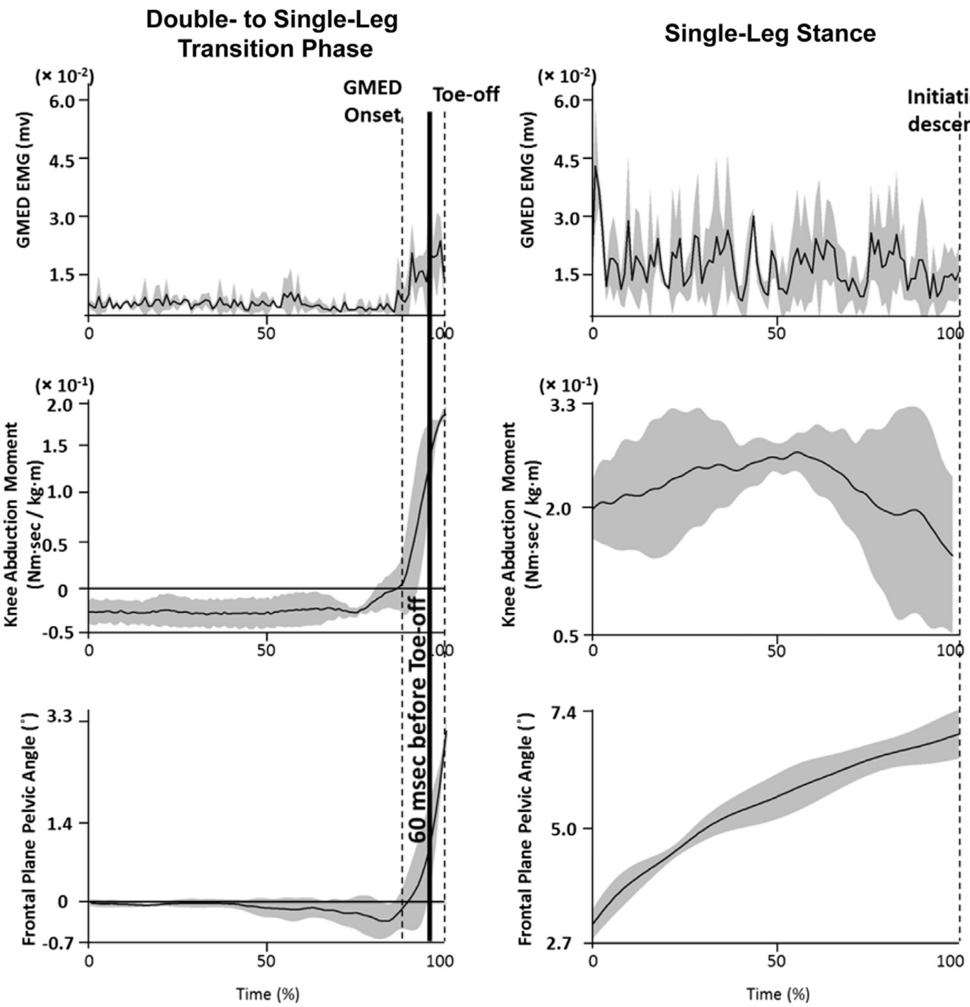

Figure 2. Gluteus medius (GMED) activation, pelvic motion, and knee kinetic patterns by movement phases. Data represent average values of all trials for a representative participant. Data from different trials were synchronized in reference to the percentage of total duration of each phase. The gray areas represent one standard deviation from the mean. The thick vertical line depicts 60 msec before toe-off. EMG = electromyography.

toe-off, and the GMED remained activated until the completion of each trial. All participants demonstrated pelvic obliquity instead of pelvic drop at toe-off. Statistical analyses showed that the magnitude of GMED activity over 60 msec prior to toe-off was negatively correlated with net change of knee abduction moment (r_s (18) = −0.303, $P < .001$) and positively correlated with pelvic obliquity (r_s (18) = 0.361, $P < .001$) (Figure 3). This finding indicates that the participants who had greater activity levels of GMED 60 msec before toe-off experienced greater pelvic obliquity and less increase of knee abduction moment during the single-leg stance phase. On the other hand, the onset of GMED was not significantly correlated with net change of knee abduction moment (r_s (18) = 0.109, $P = .105$) or pelvic obliquity (r_s (18) = −0.058, $P = .389$). The net change of pelvic obliquity and knee abduction moment were not significantly correlated with each other; however, the P value was very close to being statistically significant (r_s (18) = −0.442, $P = .05$).

Discussion

The purpose of this study was to determine the relationship between anticipatory GMED activity and

Table 1
Descriptive data of gluteus medius onset, pelvic obliquity, and knee abduction moment during the transition to single-leg stance

Variables	Mean ± SD
GMED onset	330 ± 133 msec before toe-off
Normalized GMED EMG magnitude over 60 msec before toe-off (ratio of integrated EMG over 60 msec before toe-off to integrated EMG over 60 msec around the peak burst)	0.23 ± 0.11
Net change of pelvic obliquity during single-leg stance	3.81 ± 1.24 (°)
Net change of knee abduction moment during single-leg stance	0.049 ± 0.06 (Nm/Kg · m)

EMG = electromyography; GMED = gluteus medius; SD = standard deviation.

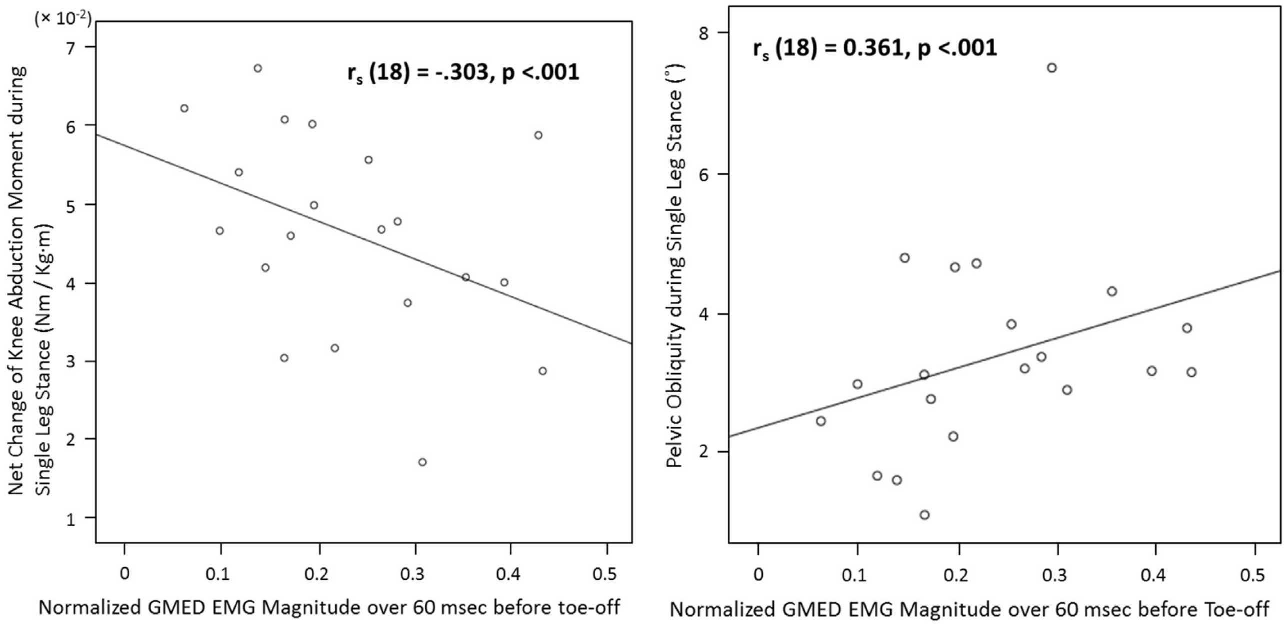

Figure 3. The relationship of anticipatory gluteus medius (GMED) activation magnitude to knee abduction moment and pelvic obliquity during single-leg stance. EMG = electromyography.

frontal plane pelvic motion and knee moment during the single-leg stance phase of a SLMS. GMED activation prior to toe-off is critical to stabilize the pelvis when it loses the support from one leg. Our results indicated that increased anticipatory GMED activation magnitude was significantly correlated with increased pelvic obliquity and decreased knee abduction moment, whereas GMED onset timing was not significantly correlated with pelvic obliquity or knee abduction moment. These results suggest that the magnitude and not the timing of GMED activation is a more important factor for protecting against excessive pelvic drop and knee abduction moment when moving from double-leg to single-leg support in healthy persons. Importantly, these results provide insights regarding how training for neuromuscular control of the GMED could be provided in a rehabilitation setting: By emphasizing the magnitude of GMED contraction before transitioning from double- to single-leg stance, lower limb positioning may be improved and knee pain may be reduced.

To our knowledge, this study is the first to investigate how GMED activation is related with both dynamic pelvic posture and knee abduction moment in a weight-bearing limb. Aminaka et al [26] reported that patients with PFP had both delayed GMED onset and greater knee abduction moment compared with healthy participants during a stair descent. These authors suggested a need to investigate a possible association between the GMED onset and knee abduction moment; however, our study could not support the correlation between these 2 variables. It is important to note that Aminaka et al [26] used different reference events for calculating GMED onset: GMED onset was calculated relative to toe-contact of the stance leg. The functional demands on the GMED for preventing excessive knee abduction moment at toe-contact on stair descent can be fundamentally different from that at toe-off in a double-leg to single-leg transition.

Toe-off during the SLMS in our study is a critical event at which pelvic drop could rapidly influence the knee abduction moment. GMED onset occurred on average 330 msec before toe-off, and all participants demonstrated pelvic obliquity; therefore, the GMED was likely activated voluntarily in anticipation of toe-off [45] with sufficient time to generate the force required to prevent pelvic drop and even counter with slight pelvic obliquity.

Previous studies [12,18,19] have only theorized that frontal plane pelvic motion would affect the knee abduction moment in a stance leg; the relationship between the 2 variables have not been directly examined prior to our study, which provides the unique assessment of the relationship between the pelvis and knee frontal plane movement. Given that GMED activation directly affects the pelvic motion, the relationship between anticipatory GMED activation and knee abduction moment could have been mediated by frontal plane pelvic motion; however, our study could not confirm such a theory because there was no significant correlation between pelvic obliquity and knee abduction moment. Nevertheless, considering that the *P* value was very close to being statistically significant ($P = .05$), it is difficult to rule out the possible relationship between the 2 variables. It is important to note that trunk leaning might have affected the location of COM position relative to the knee joint, thereby masking the effects of pelvic motion on the knee abduction moment [18,23]. Such a confounding factor was not controlled in our study. It is also important to note that other factors such as lateral trunk leaning [46] and activation of other muscles that are involved with lumbar stabilization, including quadratus lumborum, multifidus, and internal oblique [47], may contribute to pelvic obliquity during the transition from double-limb to single-limb support. It is necessary to conduct further research on how GMED activation, trunk leaning, and lumbar stability affect pelvic obliquity and knee abduction moment to truly understand what determines the knee abduction moment of a supporting leg.

This study has several limitations. The metronome used as a cue to move through the SLMS was determined to be a comfortable pace during pilot testing but may have disrupted natural movements, making it difficult to generalize the results to other activities. In addition, we did not analyze the descent of the SLMS. Asking participants to perform the descent was important, however, because it prompted them to maintain good single leg balance before descending. Finally, the results here reflect the neuromuscular control of healthy persons who were free of knee pain and/or disease. Further research into a population with knee pain and/or disease is needed to determine if this anticipatory neuromuscular control is altered and to appropriately extrapolate these findings to such a clinical population.

Conclusions

This study offers important information on the neuromuscular control of knee stability in a healthy population, which provides the basis for a comparison to a population with knee pain and/or disease. The relationship between timing and magnitude of activation related to knee abduction moment has not previously been compared in the same participants, healthy or clinical, thereby making our findings novel and relevant to clinicians. We found that increasing the magnitude of anticipatory activity in the GMED is important for reducing knee abduction moment and preventing pelvic drop during the single-leg stance phase of a SLMS. The results suggest that anticipatory GMED timing does not seem to significantly contribute to the change of knee abduction moment or pelvic obliquity during single-leg stance. Anticipatory GMED activity may have contributed to decreased knee abduction moment via its control over pelvic obliquity. To confirm such a mechanism, more research on the relationship between pelvic obliquity and knee abduction moment is warranted, in particular with other functional movements such as walking and/or the transition between sitting and standing. These findings can help clinicians focus rehabilitative efforts on increasing the strength of the gluteus medius and emphasizing, perhaps through EMG-based biofeedback training, an increased level of contraction before transitioning from double-leg to single-leg support to help prevent knee pain. Future research is necessary to determine if/how neuromuscular control of the GMED on the pelvis and knee change with knee pain and/or disease, as well as if a therapeutic intervention focused on increasing GMED activation would be helpful in improving lower limb positioning and knee pain in a clinical population.

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Disclosure

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