Journal of Orthopaedic & Sports Physical Therapy
JOSPT

Varied response to mirror gait retraining on gluteus medius control, hip kinematics, pain and function in 2 female runners with patellofemoral pain

Journal:	*Journal of Orthopaedic & Sports Physical Therapy*
Manuscript ID:	08-12-4516-CR.R3
Manuscript Categories:	Case Report
Key Words:	Knee, Running, Biomechanics/lower extremity, Electromyographic Activity

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Study design: Case report.

Background: The underlying mechanism of the changes in running mechanics after gait retraining is presently unknown. We report on changes in muscle coordination and kinematics during treadmill running and step ascent in 2 female runners with patellofemoral pain after mirror gait retraining.

Case Description: Two female runners with chronic patellofemoral pain underwent 8 sessions of mirror gait retraining during treadmill running. Subjective measures and hip abductor strength were recorded at baseline and after the retraining phase. Changes in hip mechanics and electromyography data of the gluteus medius during treadmill running and step ascent were also assessed.

Outcomes: Both runners reported improvements in pain and function that were maintained for at least 3 months. Peak contralateral pelvic drop (PRE-POST difference: Runner 1, 2.6° less and Runner 2: 1.7° less) and peak hip adduction (PRE-POST difference: Runner 1, 5.2° less and Runner 2: 6.3° less) were reduced after retraining. Kinematic reductions accompanied earlier activation of the gluteus medius relative to footstrike (PRE-POST difference: Runner 1, 12.6 ms earlier and Runner 2, 37.3 ms earlier) and longer duration of gluteus medius activity (Runner 1, 55.8 ms longer and Runner 2, 44.4 ms longer). Runner 1 transferred reduced contralateral pelvic drop to step ascent, whereas Runner 2 did not (Contralateral pelvic drop, PRE-POST difference: Runner 1, 3.6° less and Runner 2: 1.5° more; Hip adduction, PRE-POST difference: Runner 1, 3.0° less and Runner 2: 0.5° more). Both runners demonstrated earlier onset of gluteus medius activity during step ascent (PRE-POST difference, Runner 1, 48.0 ms earlier and Runner 2, 28.3 ms earlier) but only Runner 1 demonstrated longer activation duration (Runner 1, 25.0 ms longer and Runner 2, 69.4 ms shorter).

Discussion: While changes in hip mechanics and gluteus medius activity during running were consistent with those noted during step ascent for Runner 1, Runner 2 failed to demonstrate similar consistency between the tasks. Earlier onset and longer duration of gluteus medius activity may have been necessary to alter step mechanics for Runner 2.

Level of Evidence: Therapy, Level 4.

Key words: biomechanics, electromyography, knee, lower extremity, running

BACKGROUND

Running is one of the most popular and efficient forms of exercise, requiring only a pair of shoes and a place to run. Indeed, nearly 17 million Americans use running to meet the guidelines for regular exercise established by the Centers for Disease Control.[9, 20] Unfortunately, lower extremity overuse injuries are often associated with a regular running regimen. In fact, between 19.4-79.3% of runners are injured on an annual basis.[31] Patellofemoral pain (PFP) is the most common running-related injury, accounting for up to 10% of all visits to sports clinics,[16] and affects females more than twice as often as males.[31]

Growing evidence suggests that abnormal proximal mechanics may be associated with PFP in females. [12, 13, 22, 24, 25, 29, 32, 36] These abnormal mechanics, which include excessive amounts of hip adduction (HADD) [13, 22, 28, 32, 33, 36] and contralateral pelvic drop (CPD),[13, 32, 33, 36] have been noted during running and step negotiation. Increased hip internal rotation (HIR) motion has also been reported, but less frequently, in females with PFP,[13, 22, 29, 30] presumably due to the greater likelihood of error associated with transverse plane measurements. Regardless, therapies that directly target these faulty proximal mechanics, if present, may have success in the treatment of PFP in females.

As the gluteus medius is the primary musculature that controls frontal plane hip and pelvic motion, it is often targeted in clinical interventions for females with PFP. Alterations in neuromuscular control of the gluteus medius may contribute to excessive frontal plane motions of the hip. Indeed, females with PFP have been reported to demonstrate delayed onset and decreased duration of gluteus medius activity during running[42] and stair ascent.[2,8,10,16] A recent systematic review similarly concluded that there is evidence for delayed onset and decreased duration of gluteus medius activation during running and stair negotiation in females with PFP but, interestingly, there is little evidence to support alterations in amplitude of gluteus medius activation.[4] Further, increased onset latencies and reduced duration of activation of the gluteus medius have also been associated with increased hip frontal plane motions during running in females with PFP.[34] Therefore, it seems that directly addressing activation patterns of the gluteus medius may result in reductions in excessive HADD and CPD motions during functional tasks. Deficits in hip abductor strength have also been reported in females with PFP, [18,35,41] and the short term results of hip strengthening for the treatment of PFP are promising.[14, 15, 19] However, strengthening of the posterolateral hip musculature has not been shown to reduce the faulty hip mechanics associated with PFP.[19,34,45] If the underlying mechanics associated with PFP are not addressed, than recurrence may result. Therefore, interventions that directly target abnormal proximal mechanics may have promise at reducing the chronicity of PFP.

Two previous investigations have utilized gait retraining to reduce abnormal hip mechanics while also decreasing pain in female runners with PFP.[23, 37] In both studies, participants were cued to contract their gluteal musculature to accomplish reductions in excessive HADD and CPD during treadmill running. Feedback on HADD during treadmill running was provided in real time via a 3D motion capture system[23] or through the use of a full length mirror.[37] In addition to reductions in peak HADD and CPD during running, participants reported a significant decrease in pain. Interestingly, participants were able to transfer the new movement skill of reduced proximal mechanics to the untrained task of single leg squat[23, 37] and step descent.[37] Increased scores on the Lower Extremity Functional Scale (LEFS) were also reported, suggesting that participants utilized this new movement pattern in tasks other than running and squatting. All changes in pain, function, and mechanics were maintained through either 1[23] or 3[37] months post gait retraining.

Despite these promising findings, it is unknown how participants altered their frontal plane hip mechanics after gait retraining in either of these studies.[23, 37] As runners were specifically cued to contract their gluteal musculature to achieve the desired reduction in frontal plane mechanics during running, alterations of gluteus medius recruitment patterns may have resulted. While skill transfer to the untrained tasks of step descent and single leg squat was reported, it is unknown if these reductions in excessive frontal plane hip mechanics were accompanied by earlier onset and longer duration of gluteus medius activation after gait retraining.

In this report, we detail varied responses in kinematics and gluteus medius control after a gait retraining program in 2 female runners with PFP. The purpose of this paper was to describe changes in pain, self-reported function, hip mechanics, and gluteus muscle activation during running after a gait retraining program in 2 runners with PFP. A secondary purpose was to determine the 2 runners' ability to transfer changes in neuromuscular recruitment and biomechanical patterns to the untrained task of step ascent.

CASE DESCRIPTION

Two college-aged female runners with chronic anterior knee pain were enrolled in a larger gait retraining study and volunteered for this more in depth investigation. These 2 runners were the final 2 qualified subjects to participate in the larger study. To qualify for the larger study, participants were required to have PFP and excessive peak HADD during running.[37] For the purpose of this report, we opted to collect additional data in these 2 subjects to provide preliminary evidence of the effects of gait retraining for the treatment of PFP in female runners. Prior to participation, both participants signed an informed consent document approved by the University of Delaware Human Subjects Review Board.

A diagnosis of PFP was made by a physical therapist who is board certified in orthopedics (co-author RW). PFP was operationally defined as pain under or immediately around the patella, aggravated by running. Both participants scored their pain on a visual analog scale (VAS) during the last minute of a self-paced, 7-minute run on a treadmill. The pain VAS was scored such that "0" and "10" corresponded to "absent pain" and "maximal pain," respectively. Runner 1 had bilateral knee pain, but the left knee was self-rated as more severe (VAS pain: right= 2/10, left=4/10) and Runner 2 had only left knee pain during running. Accordingly, only the left lower extremity was assessed for both runners. Both participants described anterior knee pain of a duration greater than 1 year, with an insidious onset that was attributed to participation in long distance running. Each runner denied a history of patellar subluxation and/or dislocation or any previous lower extremity surgeries. In addition to scoring a pain VAS, overall function was assessed with the LEFS. The LEFS assesses one's ability (or perceived ability) to perform 20 different functional and recreational tasks on the day of testing with each task rated on a scale of “0” to “4” with “0” = “extreme difficulty or unable to perform the activity”, “1”= “quite a bit of difficulty,” “2”= “moderate difficulty,” “3”= “a little bit of difficulty,” and “4”= “no difficulty.” The LEFS has previously been validated in PFP populations and a minimum clinically important difference of 9 points has been reported.[6] On the LEFS, both runners indicated at least “moderate difficulty” running on even and uneven surfaces, making cutting maneuvers during running, deep squatting, extended standing, extended sitting, and hopping. Runner 1 also indicated moderate difficulty with negotiating a flight of stairs whereas Runner 2 indicated “a little bit of difficulty.” Demographics, running experience, duration of PFP, running volume at time of enrollment, and pain VAS and LEFS scores are detailed in **TABLE 1**. Prior to enrollment, Runner 1 did most of her running on flat pavement and hilly trails and Runner 2 did the majority of her running on either a treadmill or outside on flat pavement.

Physical examination results were nearly identical for both runners. Clustered findings for patellofemoral pain (sensitivity 60%, specificity 85%), as per Cook et al, were positive with anterior knee pain reproducible with peripatellar palpation, resisted knee extension in slight knee flexion (sensitivity 39%, specificity 82%), a positive patellar compression test (sensitivity 68%, specificity 54%), and painful deep squatting.[10] During these patellofemoral joint tests, Runner 1 indicated that her pain (left greater than right), felt in the lateral aspect of her patellofemoral joint bilaterally, was reproduced; whereas runner 2 described her pain as originating directly in the center of the left retropatellar area. Both participants had non-tender patellar tendons, inferior pole of the patellae, tibial tuberosities, and patellar fat pads on their symptomatic knee.

The distal iliotibial band of each participant was non-painful. Varus and valgus stress tests, as well as Lachmann's[5] and posterior drawer tests[27] were negative. Finally, both runners had negative McMurray tests for meniscal pathology.[1] These tests were all part of the inclusion criteria of the larger study in which we focused on a homogenous population: college-age, female runners with PFP.[37]

Runners were prepared for baseline instrumented motion analysis. These methods are described thoroughly elsewhere and will only be briefly described here.[37] Thirty retroreflective markers were attached to the pelvis and the affected lower extremity for analysis of kinematics. Movement patterns of the uninvolved limb were not analyzed. The positions of all anatomical markers were recorded with a marker placement device. This device has been shown to improve the day-to-day repeatability of marker placement with intraclass correlation coefficient values of 0.9 or greater and a standard error of measurement of 2° for all hip kinematic variables when using this device.[21] Therefore, we operationally defined a measurable change in kinematics as 2°. Both runners wore standard neutral lab shoes (Nike Pegasus, Beaverton, OR) for movement analysis. For the analysis of gluteus medius muscle activation patterns, surface electromyography (EMG) data were collected using a Motion Lab Systems MA300 system (Motion Lab Systems, Baton Rouge, LA). First, subjects were prepared for electrode placement by thoroughly cleaning the skin with isopropyl alcohol and abrading the skin. A surface disposable gel silver-silver chloride electrode with a 22 mm interelectrode distance (Norotrode 20, Myotronics, Kent WA) was mounted on a snap EMG preamplifier (MA-420, Motion Lab Systems). The electrode was placed over the gluteus medius, approximately 3 cm distal to the iliac crest and 5 cm posterior to the anterior superior iliac spine.[11] Care was taken to align the electrodes with the visualized orientation of the gluteus medius fibers. Proper electrode placement was confirmed by palpation of the muscle belly while the subject elevated the contralateral pelvis in single leg stance and by examining the signal as the subject performed a series of standing resisted straight leg raises in abduction and flexion. Satisfactory electrode placement on the gluteus medius was confirmed when the appropriate EMG signal occurred only during resisted straight leg raise hip abduction in standing, with nominal cross talk during resisted hip flexion.

Prior to collection of running data, a resting EMG reference trial was collected with a sampling rate of 1000 Hz and a bandwidth of 500 Hz. After a 5 minute, self-paced warm-up, each runner ran at 2.8 m/sec on an instrumented treadmill (AMTI, Watertown, MA) while kinematic (VICON, Oxford, UK), ground reaction forces, and EMG data were collected. Data on 15 consecutive strides were collected. All kinematic and kinetic data were sampled at 200 Hz, and 1000 Hz, respectively. In addition, each participant's running mechanics were recorded with a standard video camera for patient education during subsequent training sessions. To analyze skill transfer to an untrained functional task, data were also collected as the subjects ascended a 10-in (25.4 cm) instrumented step. Skill transfer was operationally defined as post-retraining changes in neuromuscular control of the gluteus medius and hip kinematics of at least the same magnitude as noted during running. Step ascent speed was standardized to a 1 Hz count. Seven trials were collected for analysis of step ascent mechanics.

Poor hip strength may inhibit a runner's ability to make the changes in mechanics prescribed in a gait retraining program. Thus, we chose to assess isometric hip abductor strength in these 2 runners at baseline and post-retraining. Peak hip abduction strength was measured in sidelying with a handheld dynamometer (Nicholas, Lafayette, IN) (intrarater $ICC_{3,1}$=0.96).[35] The dynamometer was stabilized against the distal thigh with straps to eliminate the potential effect of examiner strength.[7] The best of 3 maximal effort trials was used for analysis. Strength values were normalized to body weight and lever arm length (%Bw*m). The lever arm length was defined as the distance from the center of the greater trochanter to the point of application of the dynamometer.[35]

Both runners attended a total of 8 gait retraining sessions over the course of 2 weeks.[37] During all sessions, runners trained at their self-paced speed (Runner 1= 2.5 m/sec, Runner 2 = 2.4 m/sec). During their first training sessions, the runners were shown their baseline video and educated about their abnormal hip mechanics. Visual feedback during running was then provided by a full length mirror that was placed directly in front of the treadmill (**FIGURE 1**). Participants received scripted verbal cueing at the beginning of each session to directly address faulty components of their running gait. These cues consisted of "run with your knees apart with your kneecaps pointing straight ahead" and "squeeze your buttocks." A faded feedback paradigm was used to encourage internalization of the new movement skill (**FIGURE 2**). In this training schedule, both runtime and feedback time were gradually increased concurrently from 15 minutes to 24 minutes between visit 1 and visit 4 (week 1). However, during the last 4 visits (week 2), both visual and verbal feedback was gradually removed so that by the last visit, subjects ran for 30 minutes while only receiving feedback for 3 minutes. This removal of feedback was done to shift dependence from external to internal cues to facilitate acquisition of the desired motor pattern.[38] By following this retraining schedule, Runner 1 ran a total of 11.7 km and Runner 2 ran 11.1 km during week 1. During week 2, Runner 1 ran 17.6 km and Runner 2 ran 16.8 km. To strictly control the dosage of feedback, the runners were not permitted to run on their own outside of the scheduled training sessions. In addition, subjects were monitored closely for any maladaptations such as running with a widened base of support, which could potentially decrease the knee external adduction moment, or excessive toeing out, which could increase the quadriceps angle.

During each retraining session, several subjective measures were collected to monitor each subject’s response to the retraining protocol. Subjects were asked to rate their pain on the VAS during the last minute of treadmill running. Additionally, subjects were asked to rate “how hard is this new running style?” and “how unnatural is this new running style?” These subjective measures of perceived effort and unnaturalness were rated on a scale of 0-10, with “0” corresponding to “no effort” and “natural ,” and “10” corresponding to “maximal effort” and “unnatural,” respectively.

An instrumented gait and step ascent analysis was repeated at the conclusion of the 2-week gait retraining program. Markers were replaced in their pre-recorded positions using the marker placement device. Running and step ascent data were collected in the same manner as during the baseline visit. Pain was rated at the end of treadmill running data collection and LEFS data were also recorded. Hip abduction strength measures were also collected.

Upon conclusion of the retraining phase of the study, both runners returned to their normal running routines. Follow-ups were conducted at 1-month and 3-months post-retraining to obtain VAS pain and LEFS scores. When scoring pain at the 1-month and 3-month time intervals, the runners were asked to score their pain during their most recent run whereas the LEFS was scored on their ability (or perceived ability) on the day of assessment.

Data Processing

Kinematic and kinetic data were processed with Visual 3D software (C-Motion, Bethesda, MD). All kinematic, instrumented treadmill, and instrumented step data were filtered with an 8-Hz, 30-Hz, and 50 Hz low-pass, 4th order, zero-lag Butterworth filter, respectively. Only the stance phase of running was analyzed and variables were indexed to their peak values. Stance for both running and step ascent was determined using a 50-Newton vertical ground reaction force threshold. We chose a stance determination of 50-Newtons due to the higher baseline noise associated with an instrumented treadmill.[26] Stance during running terminated with toe-off whereas the step ascent event was terminated when the stance knee reached peak knee extension at the top of the step.

Due to the potential effect that variability of the velocity and duration of the step ascent may have on EMG timing variables, we developed an algorithm to choose acceptable trials. This was done to reduce between trial and between day variability. In this algorithm, the mean vertical velocity of the sacral marker during the 7 step ascent trials for pre- and post-testing sessions was pooled separately for each subject. Any trial that exceeded 1 standard deviation above the pooled mean resulted in rejection of that trial (pooled means (1 SD): runner 1= 3.01 m/sec (0.11), runner 2= 2.48 m/sec (0.18). This algorithm resulted in 3 to 5 acceptable trials for the step ascent task for each testing session.

Customized software (LabVIEW 8.0, National Instruments, Austin, TX) was used to extract the discrete variables of interest from individual curves for the motion files. Means and standard deviations of these values were calculated. The kinematic variables of interest during running were the peak values of HADD, HIR, and CPD. During step ascent, variables of interest were indexed to peak knee extensor moment. Peak internal knee extensor moment was chosen as it corresponds closely to peak quadriceps force and thus, likely relates to peak stress of the patellofemoral joint.[3, 32]

All EMG data were processed with Visual 3D software and custom LabVIEW software. Following the removal of the DC offset, the data were then filtered with a 30 Hz, highpass Butterworth bipole filter. Next, a linear envelope was created by rectifying each signal, applying a 6 Hz, lowpass Butterworth bipole filter, and subtracting the resting mean. For each trial, a 250 ms window prior to footstrike was analyzed. Muscle activation onset was defined at the point when the signal exceeded a threshold of 5 standard deviations above the mean of the resting trial for at least 25 consecutive ms.[8, 34] Termination of activation was similarly delineated when the signal was less than the onset threshold for greater than 25 consecutive ms. For running and step ascent data, onset timing relative to footstrike for the gluteus medius were calculated. In addition, durations of gluteus medius muscle activation were calculated.

OUTCOMES

Both runners reported decreases in pain, effort, and unnaturalness over the course of the 8 visits of gait retraining (**FIGURE 3**). In addition, large increases in LEFS scores were noted, reflecting an increase in overall lower extremity functional ability (**TABLE 1**). The improvement in LEFS score for both runners was greater than the clinically meaningful difference of 9 points. The runners had somewhat different pain responses.

Runner 1 had a decrease in her running-related pain from 4/10 at baseline to 0.5/10 at post-retraining. During the step ascent test, Runner 1 reported a reduction in pain (VAS) and difficulty (LEFS) from 2/10 and “moderate difficulty” at baseline to 0/10 and “no difficulty” at post-retraining. At the 1 month follow-up, Runner 1 reported an increase in her VAS pain during running to 2.5/10 and 0/10 with steps, with a decrease in her LEFS score to 75/80. She attributed this increase in symptoms to returning to extensive hill running immediately post-gait retraining. Interestingly, she stated that she had considerable difficulty maintaining the new running pattern during downhill running. However, at 3 months post-retraining, Runner 1 reported that her pain had decreased to 0/10 on the VAS during running and step negotiation. On the LEFS, she reported “a little bit of difficulty,” while sitting greater than 1 hour. Her total LEFS score was 79/80. At the 3 month time interval, Runner 1 now reported considerable ease with maintaining her new running mechanics during hill running.

At post-retraining, Runner 2 had a decrease in her running-related pain from 3.5/10 and on the VAS at baseline to 0/10. Interestingly, she had no pain during the step ascent test and indicated only “little difficulty” with negotiating 10 steps on the LEFS at baseline. At post-retraining, she reported “no difficulty” on the LEFS for stair negotiation and 0/10 on the pain VAS during step ascent. Runner 2 also reported 0/10 running and step-related pain on the VAS at the conclusion of the gait retraining phase and 80/80 on the LEFS at both 1 month and 3 months post-retraining.

At baseline, both runners demonstrated excessive peak HADD during running, which we operationally defined as greater than 1 standard deviation above our normative data (mean peak HADD=18.1°, SD=1.9°). Peak HIR during running was not considered abnormal at baseline for either runner. After retraining, the runners demonstrated reductions in peak CPD (albeit only 1.7° reduction for Runner 2) and HADD during running with no changes in HIR (**TABLE 2 and FIGURES 4 and 5**). In fact, peak HADD and CPD values during running at post retraining were below our normative data (mean peak CPD= -8.0°, SD= 2.8). After retraining, EMG data revealed that both runners activated their gluteus medius earlier during running (Runner 1= 12.6 ms earlier, Runner 2= 37.3 ms earlier, (**TABLE 3, FIGURE 6**). Additionally, duration of the gluteus medius contraction increased in both participants during running (Runner 1= 55.8 ms longer, Runner 2= 44.4 ms longer).

Runner 1 successfully transferred the reduction in CPD and HADD to the untrained task of step ascent. The increase in HIR noted for this runner during step ascent was not greater than the potential for measurement error. In contrast to the change in mechanics noted in Runner 1, Runner 2 did not demonstrate kinematic changes in step ascent mechanics that were greater than the potential for measurement error, which we operationally defined as 2°. Consistent with changes in step kinematics at post-retraining, for stair ascent, Runner 1 activated her gluteus medius considerably earlier prior to footstrike after gait retraining (**FIGURE 7**). After gait retraining, Runner 1 demonstrated a longer duration of gluteus medius activation during step ascent whereas Runner 2 demonstrated a shorter duration of activation.

At baseline, the runners presented with relatively normal hip abductor strength (Runner 1= 7.0%BW*m, runner 2= 7.8%BW*m) when compared to our normative database of 41 uninjured female runners (normative mean=8.2%BW*m, SD=2.7). At post retraining, both runners demonstrated changes in hip abductor strength. Runner 1 increased her hip abduction strength by 51.4% (10.6%BW*m) whereas Runner 2 increased by 14.9% (9.0%BW*m).

DISCUSSION

These 2 cases describe a clinically applicable gait retraining method to address abnormal hip mechanics in female runners with PFP. Both participants reported reductions in pain and improvements in overall function. Improvements in hip mechanics and neuromuscular control of the gluteus medius during running, resulting from the retraining program, were consistent between the 2 participants. These changes in hip mechanics during running were accompanied by earlier onset and longer duration of gluteus medius activation. However, the inconsistent changes between runners, in regard to the kinematics and neuromuscular control of the gluteus medius during step ascent may represent a varied response to the retraining program. Specifically, Runner 1 transferred reduced HADD and CPD and earlier onset and longer duration of gluteus medius activation to the untrained task of step ascent. In contrast, Runner 2 failed to demonstrate similar evidence of skill transfer to step ascent, with no changes in kinematics and only slightly earlier onset but shorter duration of activation of the gluteus medius.

Both runners reported considerable improvements in pain and function at post-gait retraining. Interestingly, reductions in pain occurred mostly between Visits 1-3, followed by a relative plateau in pain levels during the final 5 visits. Measures of perceived effort and unnaturalness demonstrated a more linear pattern of reduction over the full 8 visits. It is unclear if the gradual removal of feedback was responsible for the reduction in effort and unnaturalness as the participants became more reliant on internal cueing. Additionally, the retraining protocol represented a considerable decrease in both runners' normal weekly training volume, particularly during week 1 of the program. Thus, the reduction in training volume may be responsible for the considerable drop off in pain levels that were noted during week 1. At the conclusion of the retraining phase, both runners reported improvements in overall function (exceeding the minimal clinically important difference for the LEFS) while reporting little to no difficulty with stair negotiation, prolonged sitting, and squatting.

Interestingly, Runner 1 reported an increase in pain at the 1 month follow-up that she attributed to difficulty maintaining the new running mechanics (reduced HADD and CPD) when trail running on hills. By 3 months, this runner reported absent pain with downhill running and with subjective reports of greater ease with the new running mechanics while traversing hills. Downhill running likely creates higher ground reaction forces, therefore, increasing the demand on the hip abductors. Future study of the ability to maintain reduced HADD and CPD kinematics and improved gluteus medius control parameters during incline/decline running after gait retraining may be warranted. It is noteworthy that this runner performed all gait retraining sessions on a treadmill with no incline while running at the same speed (2.5 m/sec), which bears little resemblance to trail running. This static type of motor learning is considered constant practice (1 task version practiced) and is effective in the early stages of motor learning.[17] However, performing the later treadmill gait retraining sessions at various inclines/declines (variable practice) may have been more effective for this participant, easing her transition to hill running.[17]

These 2 cases add to the previous work on gait retraining for women with PFP by finding that changes in activation patterns of the gluteus medius musculature accompanied the changes in hip mechanics during running. Previous mechanistic studies suggest that abnormal hip abductor recruitment is present in females with PFP.[2, 4, 8, 11, 34] Except for a slightly higher force plate threshold to determine stance, 50 versus 10N, EMG data in this present study were collected and processed using identical procedures as those used by Willson et al,[34] enabling comparisons between the 2 investigations. Willson et al[31] reported a moderate correlation between delayed onset of the gluteus medius musculature and HADD excursion in female runners with PFP. In fact, the onset delay and length of contraction for our 2 runners with PFP prior to retraining were similar to those reported by Willson et al[34] for female runners with PFP (mean (SD) onset prior to footstrike =35.2 ms (32.3), duration of contraction= 151.2 ms (57.5)). Interestingly, the gluteus medius activation parameters noted at post gait retraining for both runners compare favorably to the values reported for uninjured female runners by Willson et al[34] (mean (SD) onset prior to footstrike= 59.7 ms (32.6), duration of contraction= 193.6 ms (38.7)). Therefore, it appears that both runners accomplished normalization of activation of the gluteus medius musculature during running at post-gait retraining. Both runners indicated that they focused primarily on the cue to "squeeze the buttocks" to increase the visual distance (via the mirror) between the knees during the retraining sessions. Thus, it is possible that their focus on gluteal activation may have biased the EMG outcomes. The gluteus medius is the primary hip abductor and frontal plane stabilizer of the pelvis and a decrease in HADD was the desired kinematic change. Therefore, we feel that "squeezing the buttocks" was the appropriate internal focus.

While both subjects improved their hip mechanics during running after gait retraining, only Runner 1 successfully improved her proximal mechanics during step ascent. Runner 1 reduced her CPD and HADD by 3.6° and 3.0°, respectively, during step ascent. These kinematic reductions were of similar magnitude to those noted during running following gait retraining for this participant. Accompanying the improvement in proximal mechanics, Runner 1 also demonstrated an earlier onset of gluteus medius activation during step ascent that was equivalent to that noted during running. Cowan et al[11] previously reported delayed onset of the gluteus medius during step ascent in females with PFP compared with healthy controls.[11] The difference in gluteus medius onset timing between females with and without PFP reported by Cowan (difference= ~50 ms) was approximately the same difference from baseline to post-retraining for Runner 1 (48.0 ms).

In contrast, for Runner 2, onset of the gluteus medius was only slightly earlier and with shorter duration than at baseline after gait retraining. Coupled with the lack of kinematic changes noted with step ascent, it appears that Runner 2 failed to transfer the improvements noted during running to a step ascent task. It may be that larger changes in gluteus medius onset timing were necessary to result in changes in hip kinematics during step ascent. Finally, we are unsure why duration of gluteus medius activation during step ascent in Runner 2 decreased at post-gait retraining. We analyzed step ascent mechanics on a single step and considerable efforts were made to control the velocity of the movement. Sequential stepping on a flight of stairs may result in a more continuous movement and may be a more valid means to assess muscle activity duration. However, the decreased duration of gluteus medius activity during step ascent by Runner 2 is consistent with the lack of kinematic changes for this individual.

At baseline, the runners in this report both presented with normal hip abductor strength, yet excessive HADD motion during running. Increases in hip abductor strength were noted after the brief 2-week retraining intervention. These increases in hip abductor strength were surprising and unexpected. Changes in strength over such a brief period were likely due to enhanced neuromuscular control of the gluteus medius, rather than actual increases in cross sectional area (hypertrophy).[18] The runners in this study both demonstrated changes in neuromuscular recruitment of the gluteus medius during running after receiving muscle coordination training during the activity. Thus, neuromuscular programs that aim to alter the timing of the gluteus medius and hip mechanics may have greater success if neuromuscular training is conducted while an individual is performing the specific task of interest. Underscoring this point, Runner 1 demonstrated changes in both the neuromuscular control of the hip as well as improved hip kinematics, as operationally defined, during step ascent whereas Runner 2 did not. Runner 2 may have required specific neuromuscular coordination training during step ascent to alter gluteus medius control of HADD.

The influence of pain on mechanics must also be considered. Runner 1 reported 2/10 pain at baseline during step ascent testing, whereas Runner 2 did not experience pain. Runner 2 may have lacked the pain stimulus to prompt any change in mechanics during the step ascent. The presence of pain during a task may provide the stimulus needed to cue changes in mechanics, particularly in untrained tasks. In addition, Runner 2's frontal and transverse plane mechanics during step ascent were not as excessive as those seen in Runner 1. Therefore, a floor effect may have been present preventing reduction of these kinematic values. Finally, we did not collect data on the opposite limb. Therefore, we are unable to report possible changes in mechanics or gluteus medius control in the opposite limb.

CONCLUSION

These 2cases present preliminary data that changes in knee pain, function, hip mechanics, gluteus medius control, and hip abductor strength occurred after a 2 week gait retraining program. The 2 cases demonstrated a varied response as far as the skill transfer of improved hip mechanics and gluteus medius activation to the task of step ascent. Further investigations, utilizing larger sample sizes, are necessary to further study the ability of gait retraining to alter faulty neuromuscular recruitment patterns across tasks.

Acknowledgements

The authors would like to acknowledge Allison Altman and Rebecca Fellin for assistance with writing the processing code for the electromyography data and the funding support by the: Foundation for Physical Therapy Promotion of Doctoral Studies I and II, Drayer Physical Therapy Institute, DOD W911NF-05-1-0097, and NIH 1 S10 RR022396.

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	Runner 1	Runner 2
Age (years)	23	20
Running distance/week (km)	27.4	32.2
Body mass index (kg/m^2)	22.6	20.2
Years reported running consistently	2	6
Reported duration of symptoms (months)	30	12
VAS pain score at baseline (0-10)	4/10	3.5/10
VAS pain score at post-retraining (0-10)	0.5/10	0/10
VAS pain score at 1 month post-retraining (0-10)	2.5/10	0/10
VAS pain score at 3 months post-retraining (0-10)	0/10	0/10
LEFS at baseline (x/80)	67/80	63/80
LEFS at post-retraining (x/80)	78/80	80/80
LEFS at 1 month post-retraining (x/80)	75/80	80/80
LEFS at 3 months post-retraining (x/80)	79/80	80/80

TABLE 1: Participant demographics, scores for pain visual analog scale (VAS) during running, and the Lower Extremity Functional Scale (LEFS).

	Run			Step Ascent		
Runner 1	**PRE**	**POST**	**PRE-POST Difference**	**PRE**	**POST**	**PRE-POST Difference**
CPD	-6.4°	-3.8°	+2.6°	-10.5°	-6.9°	+3.6°
HADD	20.8°	15.6°	-5.2°	16.9°	13.9°	-3.0°
HIR	-1.1°	1.5°	+1.4°	-9.9°	-5.4°	+4.5°
Runner 2	**PRE**	**POST**		**PRE**	**POST**	
CPD	-8.9°	-7.2°	+1.7°	-12.6°	-14.1°	-1.5°
HADD	22.5°	16.3°	-6.3°	14.1°	14.6°	+0.5°
HIR	7.7°	6.2°	1.5°	-1.8°	1.4°	+3.2°

TABLE 2: Kinematic values during running and step ascent for the two cases. Values during running are peak values during stance phase whereas values during step ascent are indexed to peak knee extensor moment. *Abbreviations: CPD, contralateral pelvic drop; HADD, hip adduction; HIR, hip internal rotation*

	Onset (ms)			Duration (ms)		
Running	**PRE**	**POST**	**PRE-POST Difference**	**PRE**	**POST**	**PRE-POST Difference**
Runner 1	-26.1	-38.7	-12.6	134.9	190.7	+55.8
Runner 2	-21.0	-58.3	-37.3	186.3	230.7	+44.4
Step Ascent	**PRE**	**POST**	**PRE-POST Difference**	**PRE**	**POST**	**PRE-POST Difference**
Runner 1	-83.7	-131.7	-48.0	852.3	877.3	+25.0
Runner 2	-27.7	-56.0	-28.3	769.7	700.3	-69.4

TABLE 3: Gluteus medius activity at baseline and post-retraining for running and step ascent. Onset is referenced to footstrike so that a negative value indicates activation prior to footstrike.

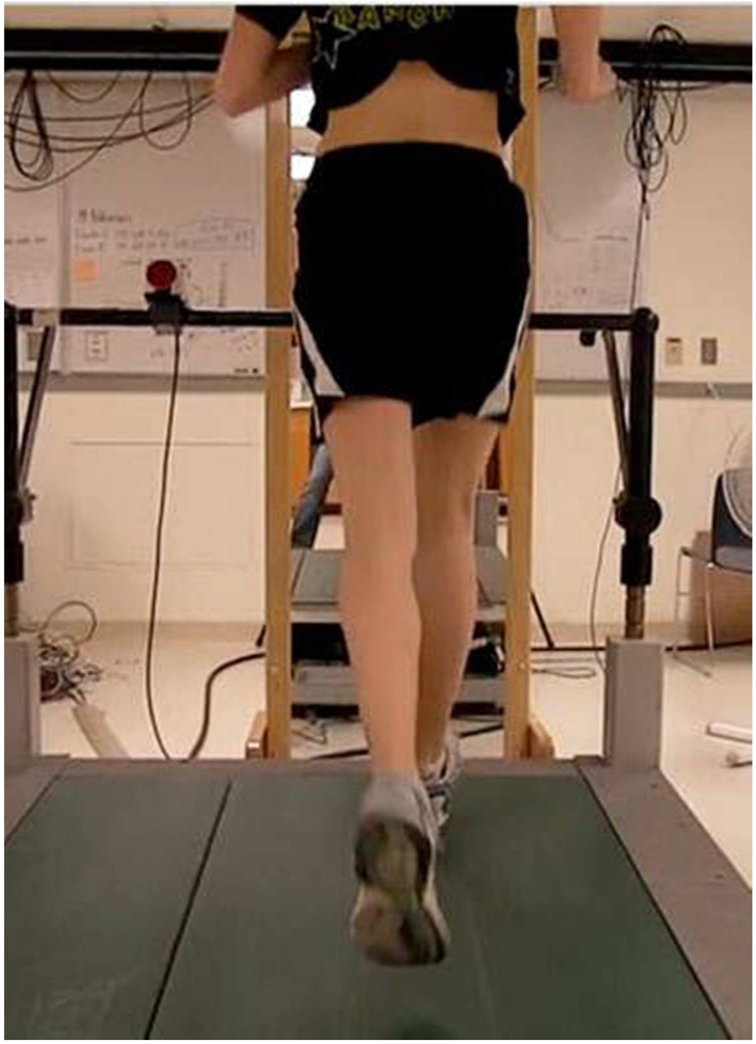

FIGURE 1. Runner 2 monitoring lower extremity alignment in a full-length mirror during gait retraining.

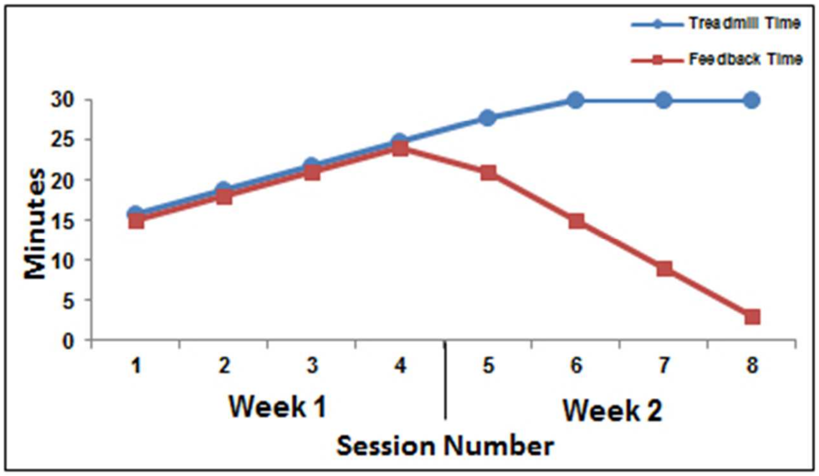

Figure 2: The gait retraining schedule. Runtime and feedback time increased concurrently through the 4th visit. During visit 5-8, runtime increased to 30 minutes while feedback was faded.

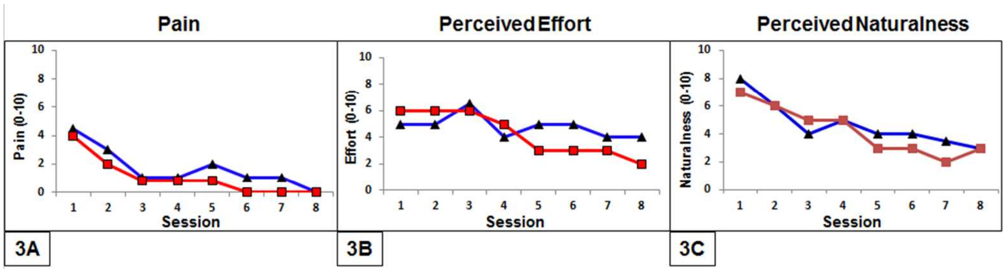

FIGURE 3. A) The majority of the reduction in pain occurred during visits 1-3. "0" and "10" correspond with "absent" and "maximally", respectively. B) Perceived effort to make the changes in running kinematics decreased slowly over the course of the 8 visits. "0" and "10" correspond with "absent" and "maximally", respectively. C) Both runners reported a steady decrease in the perceived unnaturalness of the new running technique over the course of the 8 retraining visits. "0" and "10" correspond with "natural" and "unnatural", respectively.

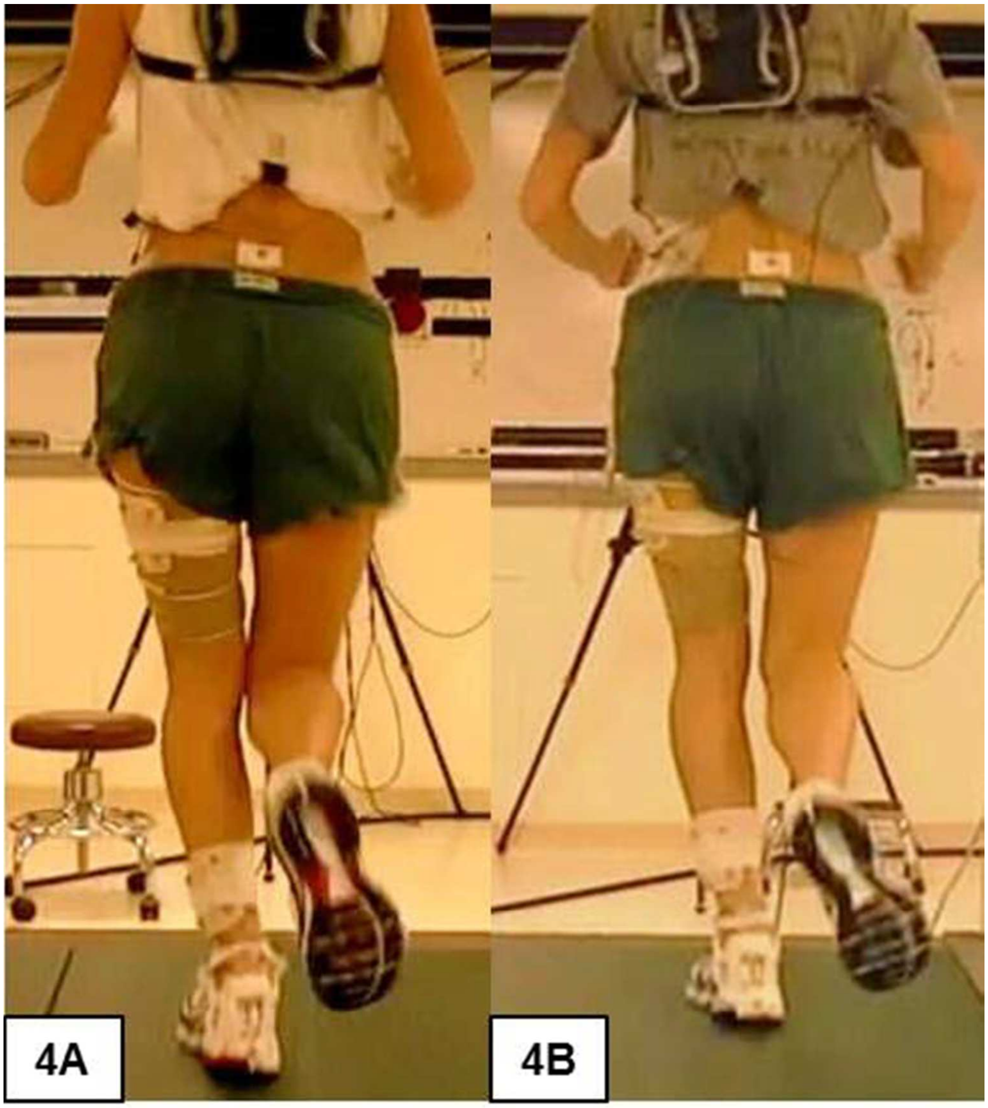

FIGURE 4. A) Runner 1 at Pre-gait retraining and B) post-gait retraining. Note the increase in space between her knees suggesting a decrease in hip adduction and a decrease in apparent dynamic genu valgus. Also note the reduction in contralateral pelvic drop.

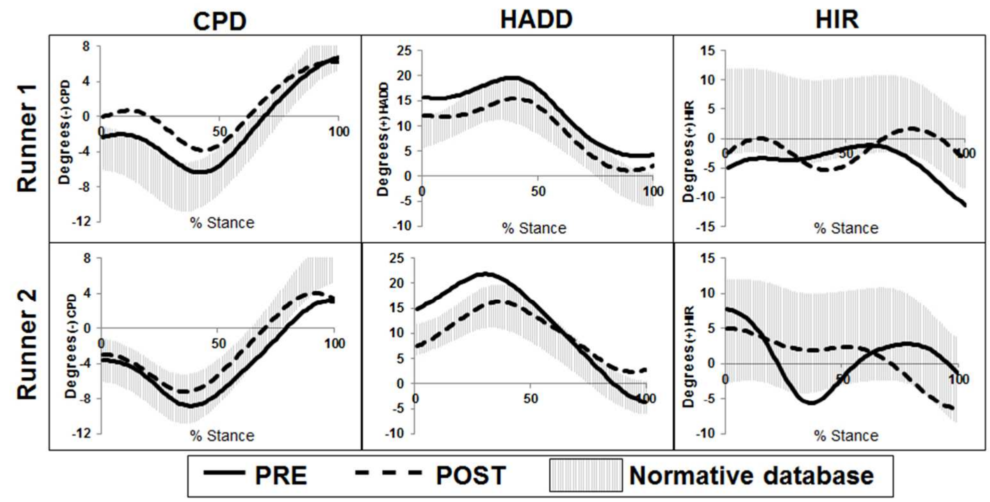

FIGURE 5: Kinematic changes for both runners. The shaded area represents our normative database of the mean of 40 male and female runners, ±1 standard deviation. *Abbreviations: CPD, contralateral pelvic crop; HADD, hip adduction; HIR, hip internal rotation.*

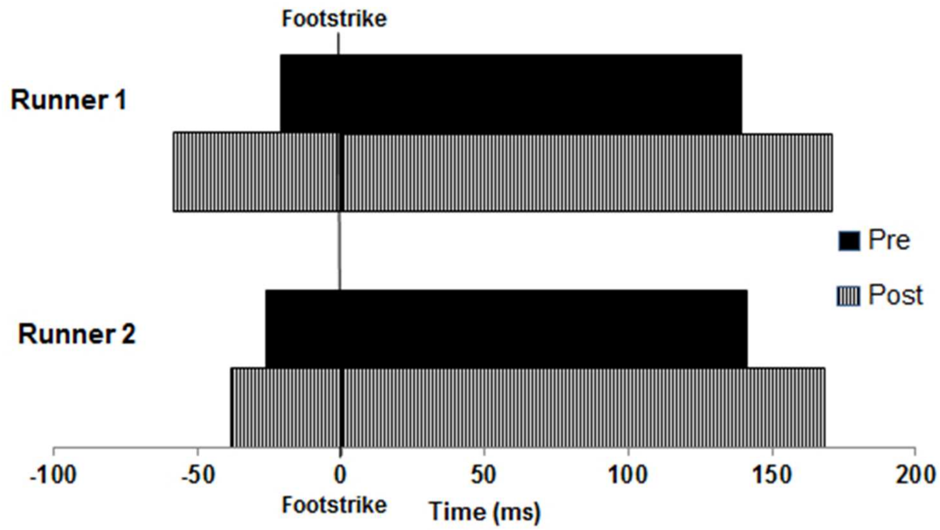

Figure 6: Gluteus medius activation during running, relative to footstrike. Both runners demonstrated earlier onset and longer duration of the gluteus medius at post-retraining.

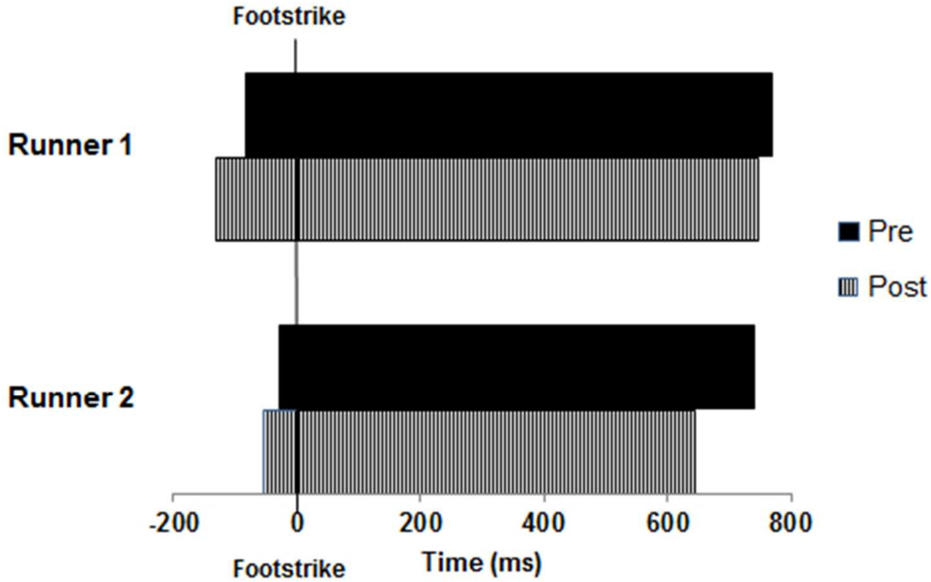

FIGURE 7: Gluteus medius activation during step ascent, relative to footstrike. Runner 1 demonstrated earlier onset and longer duration of gluteus medius activity. In contrast, Runner 2 demonstrated only slightly earlier onset and shorter duration of the gluteus medius. Note that Runner 2's onset timing of the gluteus medius occurs considerably later than Runner 1 at both time points.