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Hip muscle response to a fatiguing run in females with iliotibial band syndrome

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ABSTRACT

Impaired hip muscle function has often been cited as a contributing factor to the development of iliotibial band syndrome (ITBS), yet our full understanding of this relationship is not well established. The objective of this study was to examine the effect of fatigue on hip abductor muscle function in females with ITBS. Female runners, 20 healthy and 12 with a current diagnosis of ITBS, performed a treadmill run to fatigue. Prior-to and following the run to fatigue, gluteus medius strength and median frequency values (an indicator of fatigue resistance) were measured. Additionally, onset activation timing of the gluteus medius and tensor fascia latae was measured during overground running. Both healthy and injured runners demonstrated decreased gluteus medius strength following the run to fatigue ($p = 0.01$), but there was no interaction between groups ($p = 0.78$). EMG onset activation timing did not differ between groups for the gluteus medius ($P = 0.19$) and tensor fascia latae muscles ($P = 0.52$). Injured runners demonstrated decreased gluteus medius initial median frequency values suggestive of fatigue ($P = 0.01$). These findings suggest that the gluteus medius muscle of female runners with ITBS does not demonstrate gross strength impairments but does demonstrate less resistance to fatigue. Clinicians should consider implementation of a gluteus medius endurance training regimen into a runner's rehabilitation program.

1. Introduction

Iliotibial band syndrome (ITBS) is the second most common running injury and the leading cause of lateral knee pain in runners (Taunton et al., 2002). While symptoms of ITBS tend to present themselves at the lateral knee, the role of the hip has been investigated, with studies showing conflicting evidence as to whether or not differences in hip strength are associated with its presence (Fredericson et al., 2000; Grau, Krauss, Maiwald, Best, & Horstmann, 2008; Mucha, Caldwell, Schlueter, Walters, & Hassen, 2017; Niemuth, Johnson, Myers, & Thieman, 2005). During loading response, a large contribution from hip musculature is required to overcome large external hip adduction moments (Novacheck, 1998). Inability of hip musculature to counter the external adduction moment, whether due to weakness or neuromuscular dysfunction, is suggested to be a factor in the development of ITBS (Fairclough

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et al., 2007; MacMahon, Chaudhari, & Andriacchi, 2000; Niemuth et al., 2005). Weakness or altered activation timing is theorized to result in increased stance phase hip adduction angles, thus placing the iliotibial band (ITB) on stretch, resulting in compression at the lateral femoral epicondyle (Fairclough et al., 2007). Prospectively and retrospectively, studies have supported this increase in stance phase hip adduction in runners with ITBS (Aderem & Louw, 2015; Ferber, Noehren, Hamill, & Davis, 2010; Foch, Reinbolt, Zhang, Fitzhugh, & Milner, 2015; Noehren, Davis, & Hamill, 2007). Still other work in runners with ITBS has documented no change in hip adduction angles(Baker, Souza, Rauh, Fredericson, & Rosenthal, 2018) or decreased hip adduction angles (Brown, Zifchock, Hillstrom, Song, & Tucker, 2016) as a result of fatigue. While some studies have proposed hip abductor weakness as a contributor to altered hip adduction angles or ITBS status (Ferber et al., 2010; Fredericson et al., 2000; Mucha et al., 2017; Noehren et al., 2007), other studies have not found a relationship between these variables (Foch & Milner, 2014; Foch et al., 2015; Grau et al., 2008; Noehren, Schmitz, Hempel, Westlake, & Black, 2014) suggesting that further investigation into this area is needed.

Fatigue has been shown to result in kinematic and kinetic changes in runners with ITBS (Baker et al., 2018; Brown et al., 2016; Miller, Lowry, Meardon, & Gillette, 2007) as well as electromyographic changes in healthy runners (Boccia et al., 2017). Little is known as to the effects of fatigue on hip muscle function in runners with ITBS. One characteristic of fatiguing muscle is a shift of the electromyographic (EMG) median power frequency from higher to lower frequencies during a submaximal isometric contraction (De Luca, 1997; Naeije & Zorn, 1982). This frequency shift can be monitored to provide an index of muscle fatigue, which we will term “fatigue resistance”. Fatigue resistance, particularly at the gluteus medius, is a useful measure for runners with ITBS due to the high demands placed on this muscle during loading response. Of additional importance in this population of runners is how the hip abductors function during running gait. The gluteus medius and tensor fascia latae, both hip abductors, become active during pre-loading and remain on during the loading phase of running gait (Mann, Moran, & Dougherty, 1986). Activation of these muscles during terminal swing likely occurs in anticipation of loading response. This timing may be an important component of injury. While both muscles are hip abductors, the posterior fibers of the gluteus medius work to externally rotate the hip, while the tensor fascia latae is an internal rotator. It has previously been documented that runners with ITBS demonstrate increased tensor fascia latae EMG activity in the early stages of a fatiguing run, but no differences after a fatiguing run and no differences in gluteus medius or maximus activity at either timepoint (Baker et al., 2018). While this work suggests that EMG activity as a percentage of maximal voluntary isometric contraction (MVIC) does not differ between groups, alterations in EMG activation timing may be responsible for the increased hip adduction and internal rotation, as seen in runners with ITBS (Louw & Deary, 2014; Noehren et al., 2014). Exploration into hip abductor function and response to fatigue in runners with ITBS may provide additional valuable information to clarify the existing conflicts in the literature. For the purposes of this study, hip abductor function was defined using the following variables of interest: gluteus medius fatigue resistance, gluteus medius strength, and gluteus medius/tensor fascia latae onset activation timing.

The aim of the current study was to examine for differences in hip abductor function between runners currently diagnosed with ITBS and healthy controls as a result of a run to fatigue. It was hypothesized that following a run to fatigue, runners with ITBS would demonstrate a greater change in gluteus medius fatigue resistance, gluteus medius strength, and gluteus medius/tensor fascia latae overground running onset activation timing as compared with uninjured runners.

2. Methods

2.1. Participants

The convenience sample consisted of 20 healthy female runners (28.9 ± 6.1 yrs; 1.6 ± 0.09 m; 56.8 ± 5.2 kg) and 12 female runners with a current diagnosis of ITBS (32.4 ± 7.9 yrs; 1.7 ± 0.06 m; 60.6 ± 5.0 kg). Participant age ($P = 0.17$) and mass ($P = 0.06$) did not differ between groups. Runners in the ITBS group were taller ($P = 0.01$) than control runners. The study included females between the ages of 18–50 years old who were rearfoot strikers, currently running ≥15 miles/week. To assure that participants were able to comfortably run at the 8:00 min/mile pace required for the protocol, all runners were required to be able to run at least one sub-9:01 mile. With the exception of the current diagnosis of ITBS, participants were free from neuromuscular and musculoskeletal disorders for at least 6 months prior to data collection. A physician or physical therapist made the diagnosis of unilateral ITBS prior to participation in the study. The study protocol was approved by the institutional review board for human subjects’ research. Prior to data collection, informed consent was obtained from each participant.

2.2. Procedures

2.2.1. EMG instrumentation

For the capture of fatigue resistance and muscular onset timing, EMG data were collected using a 16-channel MA-300 EMG System (Motion Lab Systems, Baton Rouge, LA, USA). First, self-reported lower extremity dominance was established as the limb that the runner would use to kick a soccer ball. This method of determining lower extremity dominance has been found to have 97.7% agreement with task performance and a 96% test-retest agreement (Coren & Porac, 1978). Disposable surface gel electrodes with a 20 mm inter-electrode distance were placed on the gluteus medius and tensor fascia latae muscles of the injured limb in the ITBS group or the dominant limb of the control group. Electrodes were applied in parallel with the direction of the muscle fibers and in locations as described by Perotto, Delagi, Iazzetti, and Morrison (1994) (Table 1). Once in place, electrodes were connected via snap leads to the MA-411 EMG pre-amplifier (Motion Lab Systems, Baton Rouge, LA). Correct electrode placement was verified through resisted muscular testing as described by Perotto et al. (1994) (Table 1). Raw EMG data were pre-amplified with a gain of 20. The pre-amplified EMG signals were low pass filtered with a cutoff frequency of 2000 Hz using the internal low pass filter in the MA-300

Table 1
EMG Electrode location and placement verification activity (Perotto et al., 1994).

Muscle	Electrode location	Placement verification activity
Gluteus Medius	One inch distal to the midpoint of the iliac crest	Thigh abduction with the participant sidelying
Tensor Fascia Latae	Two fingerbreadths anterior to the greater trochanter	Thigh abduction with hip flexion

system. The EMG data were then sampled at 4800 Hz. This sampling rate was chosen because it is above the Nyquist rate of 4000 Hz for a 0–2000 Hz band limited signal, thus removing the possibility of error due to aliasing. The sampled data was then bandpass filtered from 10 to 2000 Hz (second-order Butterworth filter with the signal passed forwards and backwards yielding a fourth-order attenuation with 0° phase lag) (Baker et al., 2018). Prior to further testing, EMG and torque data during a 5-s MVIC and EMG data during a 2-s static baseline trial were collected. These values were acquired for use during fatigue resistance and overground running data analysis.

2.2.2. Strength testing

Isometric gluteus medius strength testing was captured on the Biodex System 4 (Biodex Medical Systems, Shirley, NY, USA). Participants were positioned in sidelying with their bottom leg flexed at the hip and knee. To best isolate the gluteus medius from the remaining hip abductors (tensor fascia latae, gluteus minimus), the participant's pelvis was rotated slightly forward with the test limb held in a position of approximately 15° hip abduction and slight extension (Hislop, Avers, & Brown, 2014). The dynamometer attachment was positioned 3 cm proximal to the lateral femoral epicondyle with participants stabilized by a strap positioned at the level of their pelvis. Three 5-s MVIC's were performed with 30-s rests between trials.

2.2.3. Fatigue resistance

Immediately following collection of isometric strength data, measures of gluteus medius fatigue resistance were collected in the Biodex so as to maintain inter-test positioning. Participants were asked to perform a 60-s isometric hip abduction contraction at 50% of their previously determined MVIC strength measure while EMG data of the gluteus medius muscle were collected. During data collection, visual feedback displayed on the Biodex computer monitor in the form of a line graph was displayed to assist participants in the maintenance of a 50% MVIC.

2.2.4. Running trials

Following the capture of strength and gluteus medius fatigue resistance data, runners were given a minimum 5-min rest while they were prepared for the collection of EMG onset data during overground running. During that time, passive retroreflective markers were placed on the heel and toe for the identification of gait events (Fig. 1). Additional markers were placed on specified locations on the trunk, pelvis, and lower extremities for the collection of kinematic data which has been previously published (Brown, Zifchock, & Hillstrom, 2014). A 12-camera Motion Analysis Corporation system (Motion Analysis Corporation, Santa Rosa, CA, USA) was utilized for calibration of the field and capture of three-dimensional digitized data. During overground running data collection, participants wore a neutral, laboratory-provided running shoe (New Balance 1061, New Balance; Boston, MA, USA). Video data were collected at 120 Hz. Data collection began with participants running along a 30-m runway through the data capture volume for the collection of five acceptable overground running trials. An acceptable trial was defined as one where EMG signal quality was good (i.e. no noise or motion artifact), kinematic data were available for the identification of gait events, and the runner maintained a speed of 3.35 m/s (± 10%). To ensure consistency across trials, velocity was recorded with a timer that was started and stopped by runners crossing two photoelectric beams placed 4 m apart on either side of the data capture volume.

Participants were then asked to perform a run to fatigue. This run was performed on a treadmill with participants cued to run at a pace that approximated their 5-km race pace. Prior to beginning the run, participants were educated on the use of the Borg CR10 scale for pain and the Borg Rating of Perceived Exertion Scale (RPE) to rate fatigue (Borg, 1998). Based off of past work which has suggested that Borg ratings of approximately 15 ± 2 were reported at 80% of maximal heart rate reserve (Whaley, Peter, Kaminsky, & Miller, 1997), we operationally defined fatigue as the point at which the runners indicated a rating of perceived exertion of 17/20. Every three minutes throughout the run, participants were asked to provide their verbal pain and RPE ratings. The run was terminated once runners were fatigued based upon a 17/20 rating on the Borg RPE scale (Koblbauer, van Schooten, Verhagen, & van Dieen, 2014; Qu & Yeo, 2011) or if runners rated their pain a 6/10 on the CR10 scale. Following termination, five trials of fatigued-state overground running data were collected in an identical manner as their fresh-state data. Following fatigued-state overground running data collection, retroreflective markers were removed and isometric strength and fatigue resistance testing were recollected in the same manner as previously described.

2.3. Data analysis

2.3.1. Strength

Peak hip abductor torque values were averaged across the three isometric strength-testing trials and the mean was utilized for data analysis. Data from the injured limb of participants with ITBS and from the dominant limb of control participants were utilized for data analysis.

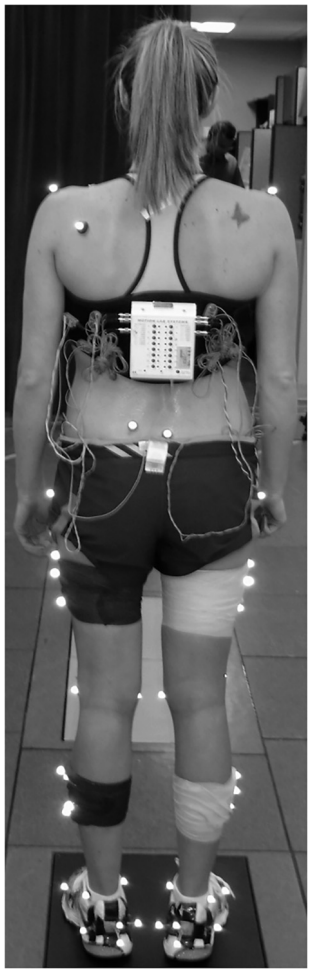

Fig. 1. Marker set with electrodes and EMG pack in place.

2.3.2. Fatigue resistance

Several of the participants were not able to sustain an isometric contraction at 50% of their MVIC for 60 s. Once participants relaxed their hip abductor muscles, the frequency of the muscle contraction would vary and affect the EMG signal's frequency content. Post-testing analysis was performed and revealed that the first 30 s of data collection were unaffected for all participants and further, the myoelectric spectral shift was seen during this time frame. Therefore, only the first 30 s of the fatigue resistance data collection were used for analysis.

Using customized code written in MATLAB (The MathWorks, Natick, MA, USA), raw EMG data were initially processed in 213 ms time segments (bins) and transformed into the frequency domain using the fast Fourier transform technique. Median power frequencies were obtained for 1.91 s bins of data and plotted versus time. The linear slope of this plot was obtained and used to express the gluteus medius "rate of fatigue" (Fig. 2). This methodology has been thoroughly described (Kondraske, Deivanayagam, Carmichael, Mayer, & Mooney, 1987; Naeije & Zorn, 1982) and its accuracy in detecting the myoelectric spectral shift verified (DeAngelis, Gilmore, & DeLuca, 1990).

2.3.3. Muscle activation timing

MVIC, resting, and overground running EMG data were processed and analyzed using customized code written in Visual 3-D (C-Motion, Inc; Rockville, MD, USA). To eliminate any baseline voltage offset, the mean of the entire raw EMG signal was subtracted from the raw EMG signal on a trial-by-trial basis. EMG data were then full-wave rectified and a linear envelope was created using a low-pass second-order Butterworth filter (forwards and backwards resulting in 0° phase lag) with a cutoff of 20 Hz (Baker et al., 2018). To determine a threshold for the onset of muscle activity, the peak activity from all trials (MVIC and dynamic running trials) and the mean EMG value of the resting trial were calculated (Serrancoli, Monllau, & Font-Llagunes, 2016). Based off of pilot work, ten percent of the difference between the maximum value and the mean resting value was added to the mean resting value and considered the threshold value (Serrancoli et al., 2016). During a running trial, when EMG activity ascended above this threshold value, the muscle was considered "on". Gluteus medius and tensor fascia latae onset during terminal swing, expressed as a percent of the

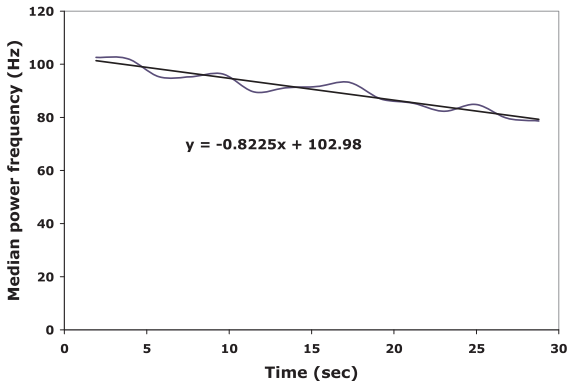

Fig. 2. Representative plot of median power frequency vs. time. Linear slope of this curve (−0.8225) indicates gluteus medius "rate of fatigue".

gait cycle, was utilized as the outcome of interest.

2.4. Statistical analysis

A 2-way ANOVA was used to examine the effects of fatigue on strength and electromyographic variables in the two experimental groups. When a significant group-by-fatigue interaction was detected, post-hoc comparisons were made using independent t-tests between groups. A significance level of $p \leq 0.05$ was established for all analyses.

3. Results

3.1. Fatiguing run

Run duration and speed did not differ between groups. Runners with ITBS and control runners performed their fatiguing run at an average pace of 3.1 ± 0.44 m/s and 3.2 ± 0.29 m/s with the run lasting an average of 25.6 ± 8.3 and 24.7 ± 7.0 min respectively. All healthy runners terminated their run as a result of fatigue (RPE rating of 17/20). Two runners in the ITBS group terminated their run due to reaching a pain rating of 6/10. For these runners, their RPE rating was 14–15/20 and 15/20, indicating "hard" on the Borg RPE scale at the time their run to fatigue was terminated. Over the course of the run, pain ratings of the healthy runners increased from an average of 0.3/10 at the start of the run to 1.25/10 at the end, associated with symptoms such as "side-stitches" and muscular soreness, but not symptoms that were suggestive of repetitive use musculoskeletal injuries. Pain ratings for the injured runners ranged from an average of 0.25/10 at the start of the run to 2.7/10 at the end and attributed mainly to ITBS symptoms.

3.2. Gluteus medius strength

There was no significant group-by-fatigue interaction (P = 0.78) for hip abductor strength (Table 2). There was no main effect of group (P = 0.53), however, there was a significant main effect of fatigue (P = 0.01). Following the run to fatigue, both healthy and injured runners demonstrated a 7.3% decrease in hip abductor strength.

3.3. Gluteus medius fatigue resistance

Due to a protocol error, fatigue resistance data from 4 control runners were collected at sampling rates of ≤1200 Hz. Due to possible undersampling of data and to avoid any aliasing, these participants' data were removed from fatigue resistance analysis. In addition, post-fatigue data from one control runner was not available for analysis as it was discovered after data collection that the ground electrode had become disconnected. Therefore, the fatigue resistance analysis was conducted on a sample of 15 healthy runners and 12 runners with ITBS. There was a significant group-by-fatigue interaction (P = 0.04) with respect to the "rate of fatigue" (linear slope of the median power frequency vs. time plot). Post-hoc t-tests analyzing simple main effects demonstrated that

Table 2
Gluteus medius strength prior-to and following a run to fatigue.

	Pre-fatigue gluteus medius strength *N*-M (SD)	Post-fatigue gluteus medius strength *N*-M (SD)	P value main effects of fatigue	P value interaction
ITBS	78.18 (14.29)	72.02 (18.58)	P = 0.01	P = 0.79
Control	76.19 (12.6)	70.39 (13.39		
P value main effect of group	P = 0.53			

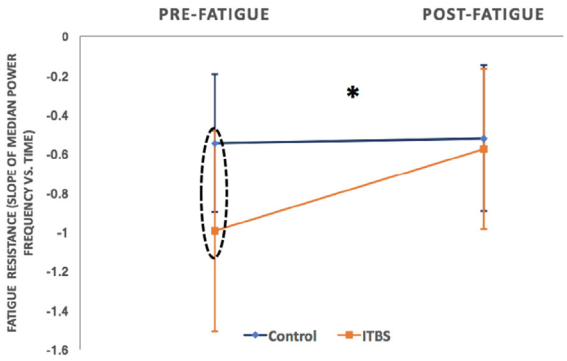

Fig. 3. Gluteus medius fatigue resistance prior-to and following a run to fatigue. * Indicates significant interaction. Indicates significant between-group difference in pre-fatigue condition.

there was a significant difference between groups in the fresh state (P = 0.01) but there were no differences when in the exerted state (P = 0.72) (Fig. 3). The presence of a pre-fatigue difference with no post-fatigue difference was surprising to the investigators. Therefore, further investigation into fatigue-related changes in the magnitude of frequency values was performed. Paired t-tests were utilized to examine the initial median frequency value for injured and healthy runners prior-to and following the run to fatigue. In healthy runners, initial median frequency values did not demonstrate a significant change from pre- to post-fatigue state (P = 0.99) while in the injured runners, there was a significant decrease in initial median frequency values as a result of fatigue (P = 0.01) (Fig. 4).

3.4. EMG onset

Due to the high-impact nature of running, prior to data analysis, raw EMG data from each runner were examined for the presence of motion artifact that could not be corrected for using filtering techniques. Based upon this visual examination, gluteus medius data from two and tensor fascia latae data from four uninjured runners were subsequently excluded from further analyses. Means and standard deviations for pre- and post-fatigue terminal swing onset activation of the gluteus medius and tensor fascia latae muscles are provided in Table 3. With a sample size of 18 uninjured control runners and 12 runners with ITBS, our data did not demonstrate a significant group-by-fatigue interaction (P = 0.19), nor any main effects of group (P = 0.97) or fatigue (P = 0.28) with respect to gluteus medius terminal swing activation timing. With 16 uninjured controls and 12 runners with ITBS, our data did not reveal a significant group-by-fatigue interaction (P = 0.52), nor any main effects of group (P = 0.36) or fatigue (P = 0.34) with respect to tensor fascia latae terminal swing activation timing.

4. Discussion

The aim of this study was to determine the effects of performing a run to fatigue on hip abductor muscle electromyography and gluteus medius strength. It was hypothesized that, as a result of fatigue, runners with ITBS would exhibit significantly different electromyographic and strength changes than uninjured runners.

Contrary to our hypothesis, this study did not identify a significant group-by-fatigue interaction when examining gluteus medius strength. It did, however, demonstrate a statistically significant decrease in hip abductor strength in both groups following the run to fatigue. This finding is not surprising as the gluteus medius muscle was likely fatigued from the treadmill run and therefore, its ability to generate torque decreased. This change, however, was consistent across groups and did not differentiate injured from uninjured

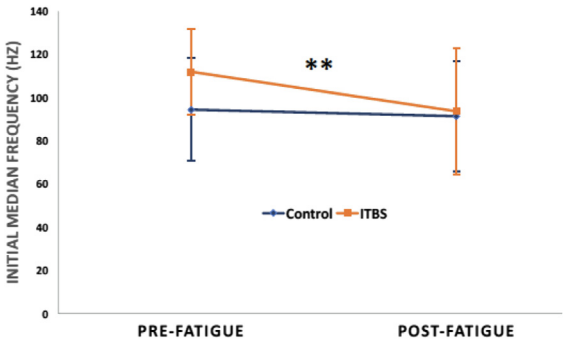

Fig. 4. Gluteus medius initial median frequency values prior-to and following a run to fatigue. ** Indicates significant change from pre- to post-fatigue in runners with ITBS.

Table 3
Gluteus medius (GM) and tensor fascia latae (TFL) terminal swing activation timing as a percent of the gait cycle, pre- and post-fatigue.

	GM-pre % gait cycle (SD)	GM-post % gait cycle (SD)	GM-P-value main effects of fatigue	GM-P value interaction	TFL-pre % gait cycle (SD)	TFL-post % gait cycle (SD)	TFL-P value main effects of fatigue	TFL-P-value interaction
ITBS	90.1 (7.7)	93.8 (6.2)	P = 0.28	P = 0.19	95.3 (6.0)	95.8 (4.5)	P = 0.34	P = 0.52
Control	92.2 (5.0)	91.8 (5.0)			93.5 (6.3)	95.6 (2.4)		
P value main effect of group	P = 0.97				P = 0.36			

runners. Previous studies have examined hip muscle strength in runners with ITBS, however, findings have been contradictory (Fredericson et al., 2000; Grau et al., 2008; Niemuth et al., 2005) leaving researchers and clinicians without conclusive evidence. Our current study found that hip abductor strength in the involved limb of runners with ITBS was not significantly different from that of a non-injured control group. These findings were consistent with several other studies whose results found there to be no differences in isometric or isokinetic strength between runners with ITBS and healthy controls (Foch et al., 2015; Grau et al., 2008; Noehren et al., 2014). Our findings are, however, in contrast to previous studies (Fredericson et al., 2000; Niemuth et al., 2005) which have documented decreased hip abductor strength in runners with ITBS or in a cohort of injured runners including those with ITBS. One factor that may explain differences in study findings was that participants in our study were not excluded based on participation in physical therapy or performance of any hip strengthening regimen. While only one participant had initiated physical therapy at the time of data collection, the remaining participants were not screened to determine if they were performing any targeted hip abductor exercises independent of a therapist's guidance. While this is a potential limitation of our study, it is also a likely representation of the true clinical population that physicians, physical therapists, or athletic trainers may encounter in their facilities. It has been suggested that weakness of the hip abductor muscles may result in increased hip adduction during the stance phase of running gait (Fredericson et al., 2000; Noehren et al., 2007). Previous work by our group has shown no significant difference in stance phase hip adduction angles in runners with ITBS while in a non-fatigued state yet documented decreased stance phase hip adduction angles in the injured runners following a fatiguing run (Brown et al., 2016). When looked at together, these results suggest that hip abductor strength deficits may play less of a role in the presentation of ITBS than previously thought. It is worth considering, however, the function of the gluteus medius muscle during the loading response phase of running gait. During this portion of the gait cycle, the hip is moving into adduction with the gluteus medius muscle functioning eccentrically to control this motion (Neumann, 2017). This study, along with previous work examining hip abductor strength in population of runners with ITBS (Grau et al., 2008; Noehren et al., 2007) have examined gluteus medius strength in an isometric manner. Generally speaking, muscles are able to generate greater forces when contracting in an eccentric manner as compared to an isometric or concentric manner (Neumann, 2017). Still, it is not unrealistic to consider that had the strength testing of the gluteus medius muscle been conducted during in an isokinetic manner testing the muscle's eccentric strength, the study outcomes may differ. Future studies should consider eccentric strength testing of the hip abductor muscles in an attempt to more accurately represent the demands of these muscles during running gait.

In support of our hypothesis, it was found that runners with ITBS exhibited significantly different changes in their gluteus medius rate of fatigue during isometric testing. The direction of this change was, however, of interest. In healthy runners, the gluteus medius rate of fatigue remained largely unchanged from a pre- to post-fatigue state, yet runners with ITBS demonstrated a decrease in the slope of their median power frequency vs. time plot following the run to fatigue. When these results are looked at in isolation, a decreased slope of this curve suggests that the gluteus medius muscle of runners with ITBS is more resistant to fatigue when in an exerted state. This finding was surprising to the investigators and prompted further investigation into the magnitude of the EMG signal's frequency component. It was found that in a post-fatigue state, runners with ITBS demonstrated a significantly lower initial median frequency value than when in a pre-fatigued state. This was in contrast to the control runners who demonstrated no change in their initial median frequency value from pre- to post-fatigue. The decreased magnitude of the initial median frequency in injured runners suggests that a fatigue-related frequency shift had already occurred and a further shift may have been dampened when examined during isometric testing. Therefore, the finding of decreased gluteus medius initial median frequency magnitude following a run to fatigue in the injured runners supports the notion that the gluteus medius muscle of runners with ITBS is less resistant to fatigue than that of their healthy counterparts. These findings highlight the importance of gluteus medius endurance training as a component of a runner's rehabilitation.

Strength and fatigue resistance data were collected during isometric contractions. The gluteus medius muscle, however, functions in an eccentric capacity during loading response. Therefore, an additional purpose of this study was to examine the activation timing of the gluteus medius and tensor fascia latae muscles during terminal swing as the muscle is preparing itself for the large eccentric demands placed on it during loading response. It was hypothesized that a neuromuscular dysfunction in runners with ITBS may change activation timing of the hip abductors. Contrary to our hypothesis, there were no significant differences between runners with ITBS and healthy controls with respect to hip abductor terminal swing onset activation timing. The run to fatigue did not affect these runners differently nor was there a main effect of group or of time when examining terminal swing onset activation timing. When collapsed across groups, the gluteus medius muscle became active on average at 91.4 and 92.6% of the gait cycle when in pre- and post-fatigue states. The tensor fascia latae became active on average at 94.1 and 95.7% of the gait cycle when in pre- and post-fatigue states. These ranges are consistent with findings from Mann and colleagues (Mann et al., 1986) who documented gluteus medius and tensor fascia latae activation at 90 and 95% of the gait cycle respectively. Our study is the first of its kind to examine the effects of fatigue on hip muscle onset timing. The gluteus medius and tensor fascia latae muscles activate during terminal swing to provide hip joint abductor stability prior-to and during loading response (Mann et al., 1986). Based on our study findings, in runners with ITBS it does not appear that the gluteus medius or tensor fascia latae muscles are early or delayed in their onset. Early activation would have indicated that the muscles were being overworked or utilized in a compensatory manner. A delay in their activation may have indicated a dysfunction that would alter kinematics and potentially act as a source of symptoms. The results from our study, however, do not support either of these scenarios and instead suggest that these muscles are becoming active at the appropriate time. Baker and colleagues similarly documented no difference in mean gluteus medius EMG activity in runners with ITBS as compared with healthy controls (Baker et al., 2018). Previous studies have documented alterations in stance phase hip kinematics present in runners with ITBS (Brown et al., 2016; Noehren et al., 2007). The results of our study do not suggest that activation timing of the gluteus medius and tensor fascia latae muscles are to blame. It is possible that it is the total activation timing as a percent of the gait cycle or the timing of stance phase cessation (rather than swing phase activation) that differentiates injured from uninjured runners. Future

studies should hypothesize on and examine these variables.

This study is not without limitations. Runners in this study performed a run to fatigue on a treadmill yet had EMG data collected during overground running. It is not known if a fatiguing run performed on a treadmill would result in altered post-fatigue overground running muscle activation. It is possible that the demands placed on the gluteus medius muscle during the treadmill fatiguing run may be less than those which would have been experienced during a fatiguing run performed overground. Recent work has demonstrated increased EMG amplitude during overground running as compared to motorized treadmill running (Montgomery, Abt, Dobson, Smith, & Ditroilo, 2016). While this recent work did not specifically examine the gluteus medius muscle, it can be hypothesized that an overground fatiguing run would have placed greater demands on the gluteus medius muscle as compared to the treadmill fatiguing run. Future studies should examine for whether fatiguing runs on a treadmill alter overground running kinematics and gluteus medius EMG activity differently than do fatiguing runs performed overground, specifically in a female running population. Additional potential limitations of this study are the standardization of shoewear and overground running speed. Runners were asked to perform their treadmill run at a self-selected speed, yet overground running data were collected at a speed of 3.35 m/s (± 10%). Further, it is possible that this standardization of shoewear may alter a runner's EMG patterns, thus affecting the results of the study. Participants were included in the study if they were diagnosed by either a physical therapist or a physician, however, study protocol did not account for how many participants were diagnosed by each profession. It is possible that participants diagnosed by a physician as compared to those diagnosed by a physical therapist may have been diagnosed based off of differing criteria and thus demonstrate a different clinical presentation. Finally, the study methodology allowed overground running to be collected within 10% of 3.35 m/s. This allows for a maximum 0.66 m/s difference between the slowest and fastest acceptable overground running paces. These allowances may affect study findings.

5. Conclusion

Our study findings suggest that the hip abductors of runners with ITBS demonstrate less resistance to fatigue than hip abductors of healthy runners. Based on the clinical presentation of ITBS, the idea that the injured runners' hip abductors are not "weaker" but less resistant to fatigue is of particular interest. Symptoms of ITBS tend not to be present at the initiation of a run, but arise and/or worsen after 20–30 min of running. These results, combined with the clinical presentation of ITBS, suggest that hip abductor endurance or fatigue resistance may play a larger role in the syndrome's etiology than strength alone. Together, data from this study suggest that the lateral knee pain experienced in runners with ITBS is more likely associated with a decreased ability of the gluteus medius muscle to resist fatigue, than with a decreased ability for this muscle to generate a maximal torque (as seen during isometric testing) or by alterations in the terminal swing onset timing of the gluteus medius or tensor fascia latae muscles. Clinically, considerations should be taken to incorporate exercises focused on gluteus medius endurance. While there lacks evidence as to the most appropriate exercise to address endurance and fatigue resistance in the gluteal muscles, is plausible that lower load higher repetition exercises, particularly those challenging the gluteus medius in an eccentric manner would be most appropriate to improve fatigue resistance. Future studies should explore the exercises most effective at improving gluteus medius endurance as well as exploring other biomechanical factors that may be affected by decreased muscular endurance.

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Declarations of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.02.002.

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