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Original Research

Stiffness of the iliotibial band and associated muscles in runner's knee: Assessing the effects of physiotherapy through ultrasound shear wave elastography

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A R T I C L E I N F O

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A B S T R A C T

Objectives: To test the hypothesis that Iliotibial Band Syndrome (ITBS) is caused by excessive iliotibial band (ITB) tension, promoted by hip abductor and external rotator weakness, and evaluate the influence of 6 weeks of physiotherapy on ITB stiffness.
Design: Interventional study with control group.
Setting: Clinical.
Participants: 14 recreational runners with ITBS and 14 healthy controls of both sexes.
Main outcome measures: Ultrasound shear wave elastography, hip muscle strength, visual analog scale pain, subjective lower extremity function.
Results: No statistical differences in ITB tension between legs as well as between patients suffering from ITBS and healthy controls were detected. Results showed significant strength deficits in hip abduction, adduction as well as external and internal rotation. Following six weeks of physiotherapy, hip muscle strength (all directions but abduction), pain and lower extremity function were significantly improved. ITB stiffness, however, was found to be increased compared to baseline measurements.
Conclusion: Shear wave elastography data suggest that ITB tension is not increased in the affected legs of runners with ITBS compared to the healthy leg or a physical active control group, respectively. Current approaches to the conservative management of ITBS appear ineffective in lowering ITB tone.

1. Introduction

Running contributes to a healthy lifestyle (Fields, 2011) and ranges amongst the most popular recreational sports activities, with one third of adult Austrians reporting to run frequently (Schwabl, 2015). The social and health benefits of running notwithstanding, overuse injuries are common (Bramah et al., 2018; Fields, 2011). The predominant location of overuse injuries in the active population is the knee, with Iliotibial Band Syndrome (ITBS) representing one of the most frequent complications (Fields, 2011; van Gent et al., 2007). The number of diagnosed cases increases with the growing popularity of recreational distance running (Fields, 2011) but the etiology of the syndrome is still unclear.

In typical ITBS cases, pain is located superior to the lateral joint line, near the lateral femoral epicondyle. It occurs in response to excessive physical activity involving cyclic motion of the lower limb, such as running or cycling. While initially assumed to be a friction syndrome (Ellis et al., 2007; Orchard et al., 1996), newer evidence suggests that ITBS is caused by excessive tone in the iliotibial band (ITB) leading to chronic compression of underlying tissues (such as fat pads or bursae) and, consequently, to inflammation and pain (Fairclough et al., 2006; Flato et al., 2017). Biomechanically unfavorable positions, such as excessive hip adduction and internal rotation, potentially associated with pelvic

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drop, as well as internal rotation of the tibia and varus torques at the knee are assumed to increase tensile strain of the ITB (Ferber et al., 2010; Flato et al., 2017; Tateuchi et al., 2016), thus also augmenting the pressure at the lateral femoral condyle (Ferber et al., 2010; Hamill et al., 2008; Powers, 2010; Tateuchi et al., 2016). In agreement with the notion that excessive hip adduction could raise ITB tension to unphysiological levels, there is strong evidence from both biomechanical and clinical studies to suggest a relationship between inadequate function of the hip abductor and external rotator muscles and several knee injuries, including ITBS (Chuter & Janse de Jonge, 2012; Fredericson et al., 2000a; Fullem, 2015; Kollock et al., 2016; Niemuth et al., 2005).

To date, the examination of ITB tension relies mostly on the clinical Ober test (Kendall et al., 2009; Ober, 1936). Originally developed to examine the relationship between tightness of the ITB and low back pain, it is also used to assess the flexibility of the iliotibial tract in the context of ITBS (Reese & Bandy, 2003). However, the validity of the test is questionable (Wang et al., 2006; Willett et al., 2016), and no techniques allowing for the direct measurement of ITB stiffness have expanded into clinical routine. Shear wave elastography (SWE) represents a novel ultrasound-based imaging modality facilitating the *in vivo* study of tissue mechanical properties. In brief, the technique relies on the application of acoustic radiation force impulses to induce tissue perturbations that propagate through the examined tissue (Gennisson et al., 2013). Using ultrafast imaging techniques, these shock waves are tracked to generate an elastographic image that yields quantitative information about tissue stiffness. Recently performed pilot studies have applied the technique to the study of the stiffness of both the ITB (Tateuchi et al., 2016) and the in-series tensor fasciae latae muscle (Umehara et al., 2015). However, no SWE studies have been performed in subjects suffering from ITBS.

In the light of the above considerations, the present study aimed to (i) test ITB stiffness and isometric hip muscle strength in a sample of subjects clinically diagnosed with ITBS for comparison with a healthy control group, and (ii) assess the effectiveness of a multimodal training program in strengthening the hip abductor and external rotator muscles and modulating ITB tone. We hypothesized that shear-wave propagation velocity and, consequently, ITB stiffness, would be significantly greater in subjects diagnosed with ITBS as compared to healthy control subjects. We further expected to find significantly decreased maximum isometric strength of the hip abductor and external rotator muscles, resulting in altered abduction/adduction and internal/external rotation ratios. A 6-week training therapy program was assumed to increase the isometric strength of the hip abductor and external rotator muscles, and lead to clinical improvements associated with a reduction in ITB stiffness.

2. Methods

We conducted a repeated measures interventional study with a control group. Measurements were performed twice: Subjects suffering from ITBS were examined before and 1–2 weeks after a 6-week treatment period, and healthy control subjects were similarly tested twice within 7–8 weeks.

2.1. Participants

A sample of 14 subjects of both sexes suffering from ITBS were recruited from within the patients presenting at a specialized sports and joint surgery clinics and via advertisements in local newspapers. Additionally, 14 healthy, physically active subjects matched for sex were recruited among students enrolled in sport science at the University of Innsbruck to serve as a control group. This sample size was determined through *a priori* power analysis ($\alpha = 0.05$, $1\text{-}\beta = 0.8$, $dz = 1$) based on previously published data of ITB stiffness (Tateuchi et al., 2016) and the assumption that ITB stiffness would be greater by more than one standard deviation in ITBS subjects.

Subjects participating in this study had to be 18–45 years old. Participants suffering from ITBS were recreational runners, with a self-reported weekly training volume of at least 20 km before the first occurrence of symptoms. The diagnosis of ITBS relied primarily on clinical examination by experienced orthopedic surgeons. Functional tests used to facilitate the differential diagnosis included the Noble (Noble, 1980; Noble et al., 1982), Ober (Ober, 1936; Wang et al., 2006) and Thomas (Harvey, 1998) tests. Additionally, MR images were acquired in the coronal and axial plane (T1: TR 800 ms, TE 20 ms/T2: TR 2250 ms, TE 80 ms; slice thickness: 2 mm; gap: 1 mm; flip angle: 90°; 256 × 192 matrix; FOV: 16 cm; 1.5 T Magnetom, Siemens AG, Erlangen, Germany) to verify the presence of edema over the lateral femoral epicondyle as well as thickening of the ITB, typically found in ITBS patients (Ekman et al., 1994), and rule out other pathologies (such as meniscal injuries) potentially causing the symptoms. Controls had to be healthy, highly physically active people (physical activity >500 min/week) with no history of ITBS. Aside from ITBS, all participants were free of pain and injury affecting the lower extremities or other knee pathologies. Participants with a BMI >30, previous operations at the knee joint, accompanying injuries diagnosed clinically or through MRI, past physiotherapy within the last 12 months as well those in whom physical therapy was not feasible due to physical or other limitations were excluded from participation.

All participants were informed about the aims and the procedure of the study prior to giving written informed consent for participation in the study. The study was approved by the Ethics Committee of the Medical University of Innsbruck (1090/2018).

2.2. Intervention

Patients were requested to refrain from running for the duration of the intervention. They underwent 6 weeks of physiotherapy in an outpatient clinic. Five therapists were specifically trained to perform treatments as recommended in the literature (Baker & Fredericson, 2016). Interventions consisted of measures aiming to decrease ITB tightness, strengthen the hip-stabilizing muscles, and improve neuromuscular control and lower extremity alignment during gait and running, respectively.

Two sessions a week were performed in-house for hands-on treatments and supervision of conditioning exercises. Training therapy interventions were tailored according to each patient's individual needs and state of recovery (Baker & Fredericson, 2016) but followed the following general principles (see Table 1):

In the first treatment sessions, hands-on techniques were applied, and patients were given instructions to correct potential pelvic drop, trunk deviations or deficits in knee alignment during walking. Myofascial techniques addressing trigger points in hip- and thigh-muscles were used with the aim to decrease the tension of the iliotibial tract (Fredericson et al., 2000b). After the resolution of symptoms, strengthening exercises were incorporated and gradually increased in intensity according to the modified strength-rehabilitation-system (KRS) (Bant et al., 2011). Emphasis in strength training was put on the gluteus medius and maximus muscles to improve leg to trunk alignment, and on hip external rotators, considering the findings of increased hip internal rotation and weakness of external rotators in runners (Mucha et al., 2017; Noehren et al., 2014). Exercises like clam shell, pelvic drop, single-leg step down, and single-leg squat were performed (Baker & Fredericson, 2016).

Table 1
Treatment plan in different phases of recovery.

Phase	Goal	Action
Acute (running/walking causes pain, swelling, continuous pain)	Alleviate pain	Discontinue painful activities, instructions on walking technique, anti-inflammatory medication
Subacute (signs of inflammation eased)	Correct myofascial restrictions, reduce ITB stress near insertion	Manual therapy (myofascial and joint techniques), foam rolling lateral thigh, stretching ITB, activate posterolateral hip muscles
Recovery strength (movements pain-free)	Pelvic control, strengthen hip abductor and external rotator muscles	Standing exercises to strengthen hip muscles, stretching and foam rolling
Return to running (all exercises pain-free and in good form)	Graded progression	Short distance running on level ground, pelvic control, soft landing

In addition to supervised physiotherapy sessions, patients were requested to perform home-based exercises, consisting of stretching and foam rolling to reduce ITB tension, on a daily basis. Static stretching exercise were performed twice a day (two sets of 60 s duration, 30 s inter-set break) (Fredericson et al., 2002; Fredericson & Weir, 2006; LaRoche & Connolly, 2006; Maeda et al., 2017). Foam rolling targeted the region between the greater trochanter of the femur and lateral knee joint line and was performed three times for 60 s (4–6 times per minute) with a break of 30 s between sets (Cheatham et al., 2017; Junker & Stöggl, 2015; Wilke et al., 2019). One additional strengthening session to be carried out at home was also prescribed, resulting in a total of three weekly strengthening training sessions. Patients were instructed to keep a training diary and document the execution of home-based training.

2.3. Outcome measures

The primary outcome measure was tissue stiffness in the distal ITB as well as the tensor fasciae latae (TFL) and gluteus maximus muscles (GM), which insert into the ITB, thus influencing its stiffness. To obtain SWE images, subjects lay supine on an examination bed with their backs slightly raised and knees rested on a support cushion (hip angle 140°–150°, knee angle ~90°). Shear wave elastography images (Aixplorer, SuperSonic Imagine, Aix-en-Provence, France) were obtained in the sagittal and frontal plane, respectively, in both legs in three locations: proximally, above the tensor fasciae latae (2 cm proximal of the greater trochanter of the femur in the direction of the anterior superior iliac spine) and gluteus maximus muscles (4.5 cm proximal of the greater trochanter of the femur in the direction of the highest point on the iliac crest), and distally above the ITB (2 cm proximal of the lateral femoral epicondyle). A 50 mm linear array transducer (SL10-2, Supersonic Imagine, France) was used. The system was run in musculoskeletal mode with a frequency of 2–10 MHz. The penetration mode and opacity were set to SWE Opt and 85%, respectively. The preset was adjusted to a depth of 1 cm for the ITB and 3 cm for the muscles. The elastic scale was limited to 600 kPa. The Q-Box was traced manually to include a maximum of muscle tissue while avoiding the myotendinous junction and fasciae, or to downsize it in order to measure the very thin ITB.

Previous studies performed in the Achilles and patellar tendon as well as the ITB have demonstrated excellent reliability of SWE measures (Tateuchi et al., 2015; Taş et al., 2017; Aubry et al., 2013; Kot et al., 2012). Regions of interest (ROI) were manually outlined (Fig. 1). During measurements, enough ultrasound gel was applied between the skin and the transducer to avoid skin deformation. The midpoint of the transducer was placed perpendicularly on the skin's surface on the ITB and muscle fibers with light pressure, and then the mode of the SWE was activated to examine the shear wave modulus of the tendon. During the acquisition in SWE mode, the transducer was kept motionless for about 5–8 s[44]. Then, the gray scale image showed the appearance of the tendon under the longitudinal section. Image quality was closely monitored throughout the measurements. When the color in the ROI was uniform and the structure of the ITB and the muscle fibers were continuously visible, the images were frozen and moved to the Q-Box to obtain the shear wave modulus (Zhou et al., 2020). Three images were captured at each measurement site of each tendon third. The mean of the elastic modulus from all 3 images was used for further analyses.

Muscle strength tests were performed using a digital, hand-held dynamometer (MicroFET 2, Hoggan Health Industries, Inc., Draper, UT). Previously published studies examining the reliability and validity of hand-held dynamometers (HHD) showed good intratester reliability (Arnold et al., 2010; Kelln et al., 2008) and moderate to high validity (Arnold et al., 2010) in comparison with isokinetic measurements for isometric strength at the hip. Hip muscle strength was measured in internal (IR) and external rotation (ER), abduction (ABD) and adduction (ADD). All strength tests were performed by a team of two examiners and followed a standardized protocol: Following 5 min of general warm-up on a cycle ergometer, subjects performed 15 unloaded repetitions of hip ABD, ADD, IR, and ER, respectively, for specific warm-up and familiarization with the test condition. Then, the isometric maximum voluntary contraction (MVC) strength was assessed. Both legs were tested in a randomized order. Subject and HHD positioning followed the recommendations provided by Thorberg and colleagues (Thorborg et al., 2010). To further improve measurement reliability, the HHD was fixed with a stabilization strap looped around the examination bed (hip ab- and adduction trials) or a vertical, wall-mounted bar (hip internal and external rotation), respectively (Fig. 2). For all MVC tests, participants performed 3 trials of 3 s duration, interspersed by 30 s of passive recovery. The 3 measures were averaged, normalized to body mass and used to calculate ER/IR and ABD/ADD ratios. In addition, VAS pain and subjective lower extremity function (LEFS) were assessed at baseline and after the treatment (ITBS) or control period of 8 weeks (control group), respectively.

2.4. Data analysis

Baseline differences in SWE and MVC data were tested for significance by means of a factorial MANOVA, considering "leg" (affected/non-dominant vs. non-affected/dominant) as within- and "group" (ITBS vs. control group) as between-subjects factor. For evaluation of the treatment effects, only the data acquired in the intervention group were considered. Since Shapiro-Wilk tests indicated violations of the assumption of normality, pre- and post-intervention data were compared by means of Wilcoxon tests. Changes in VAS and LEFS scores were tested using paired-samples t-tests and Wilcoxon tests, respectively. For significant changes, Pearson's coefficient was calculated through conversion of test statistics and reported as measure of effect size. The level of significance was set at $p \leqq 0.05$. Data analysis was performed using SPSS Statistics Version 25 (IBM Incorp., Armonk, NY, USA).

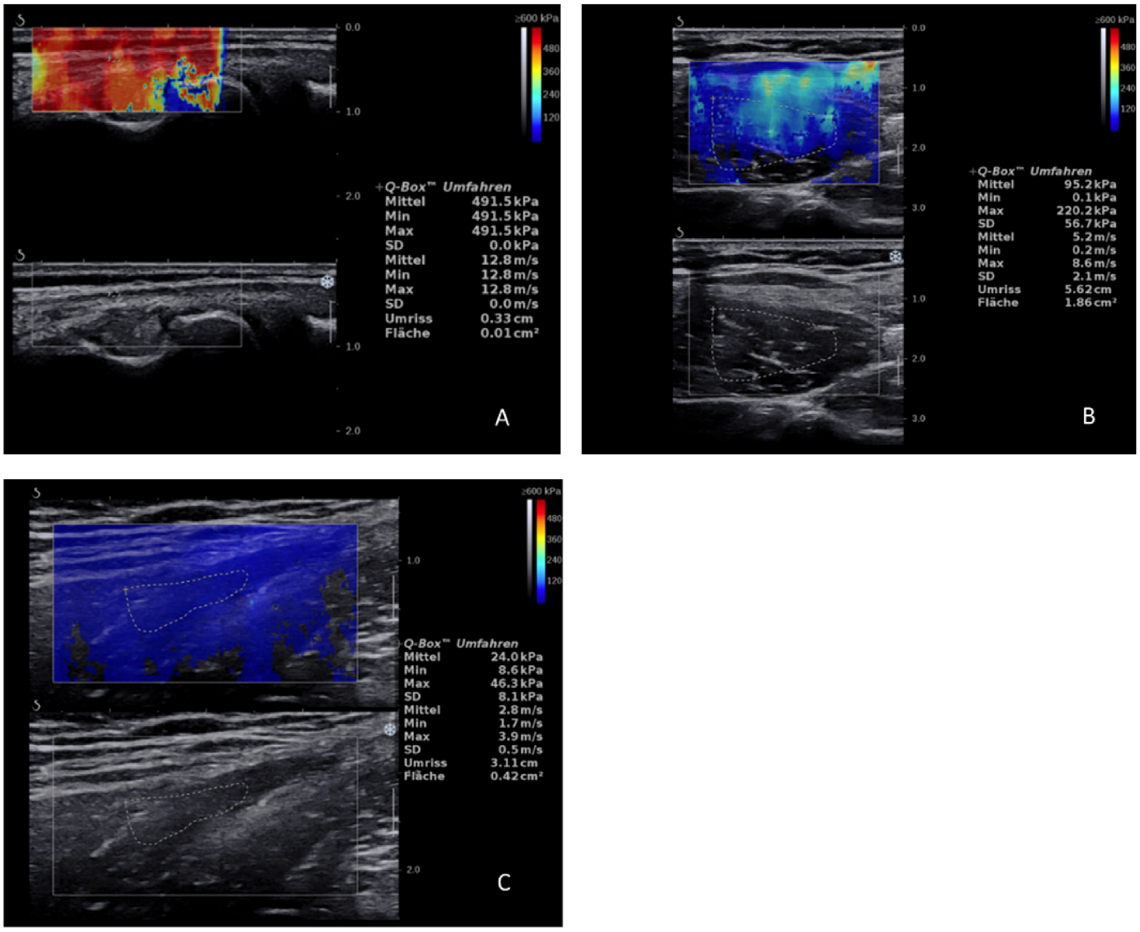

Fig. 1. Shear-wave-elastography images. Examples of images taken from Iliotibial band (A), Tensor fasciae latae (B), and Glutaeus maximus (C).

3. Results

Descriptive statistics characterizing the study sample are shown in Table 2. Four participants suffered from ITBS bilaterally. In one of them, MR imaging revealed an accompanying cartilage defect, so the data acquired in this leg were excluded from analysis. Consequently, data from 17 affected and 10 healthy legs (ITBS patients) and 14 non-dominant and 14 dominant legs (control group) were analyzed. No significant between-group differences were found in sex distribution, height and mass, but subjects in the control group (CO) were significantly younger by 5.4 years on average.

3.1. Baseline differences

MANOVA results showed a significant effect of the factor “group” on SWE propagation velocity data ($F(3,48) = 4.351$, $p = 0.009$). Tests of between-subject effects performed to follow-up this finding revealed that TFL propagation velocity ($F(1,50) = 10.416$, $p = 0.002$, $r = 0.41$) was significantly higher in control subjects. The factor “leg” ($F(3,48) = 1.296$, $p = 0.287$) and “leg × group” interactions ($F(3,48) = 0.186$, $p = 0.906$), by contrast, did not have a significant effect on the set of dependent variables.

MANOVA-based analyses of strength data (Table 3) revealed significant baseline differences in normalized MVC measures between patients and control subjects ($F(4,48) = 7.160$, $p < 0.001$). Separate univariate ANOVAs on the outcome variables showed significantly higher values in the CO group in all strength tests (ER: $F(3,51) = 18.715$, $p < 0.001$, $r = 0.52$; IR: $F(3,51) = 14{,}035$, $p < 0.001$, $r = 0.46$; ABD: $F(3,51) = 15.953$, $p < 0.001$, $r = 0.49$; ADD: $F(3,51) = 12.054$, $p = 0.001$, $r = 0.44$). Differences between legs ($F(4,48) = 0.206$, $p = 0.934$) and “leg × group” interactions ($F(4,48) = 0.503$, $p = 0.733$) were non-significant. ER/IR and ABD/ADD ratios were not significantly affected by “group” (ER/IR: $F(1,22) = 0.005$, $p = 0.946$; ABD/ADD: $F(1,22) = 0.354$, $p = 0.558$), “leg” (ER/IR: $F(1,22) = 0.984$, $p = 0.332$; ABD/ADD: $F(1,22) = 1.039$, $p = 0.319$) or “leg × group” interactions ($F(1,22) = 0.120$, $p = 0.732$).

3.2. Treatment effects

The level of pain, as measured by VAS, decreased significantly from 12.86 ± 14.40 to 4.21 ± 7.47 at rest and from 78.29 ± 14.61 to 16.86 ± 24.20 during running ($z(13) = -2.703$, $p = 0.007$, $r = 0.72$; $t(13) = 8.044$, $p < 0.001$, $r = 0.91$). After treatment, 7 out of 14 ITBS patients reported to be completely free of pain. Functional improvements, reflected by LEFS scores (baseline: 65.50 ± 6.67, post-intervention: 76.36 ± 4.81), were also found to be highly significant ($t(13) = -6.69$, $p < 0.001$, $r = 0.88$).

In the affected legs, ITB stiffness, as reflected by SWE propagation velocity, increased by 13.5% from 12.49 ± 2.97 m/s to 14.17 ± 1.36 m/s. This change over time was found to be significant ($t(16) = -2.471$, $p = 0.025$, $r = 0.53$). Changes of ITB stiffness in the non-affected leg ($t(9) = 0.150$, $p = 0.884$) as well as changes of GM and TFL stiffness in both legs were non-significant (GM aff/nd: $z(16) = -0.569$, $p = 0.569$; GM na/dom: $t(9) = 0.163$, $p = 0.874$; TFLaff/nd: $t(16) = -0.352$, $p = 0.729$; TFL na/dom: $t(9) = -0.423$, $p = 0.682$). The results are shown in Fig. 3.

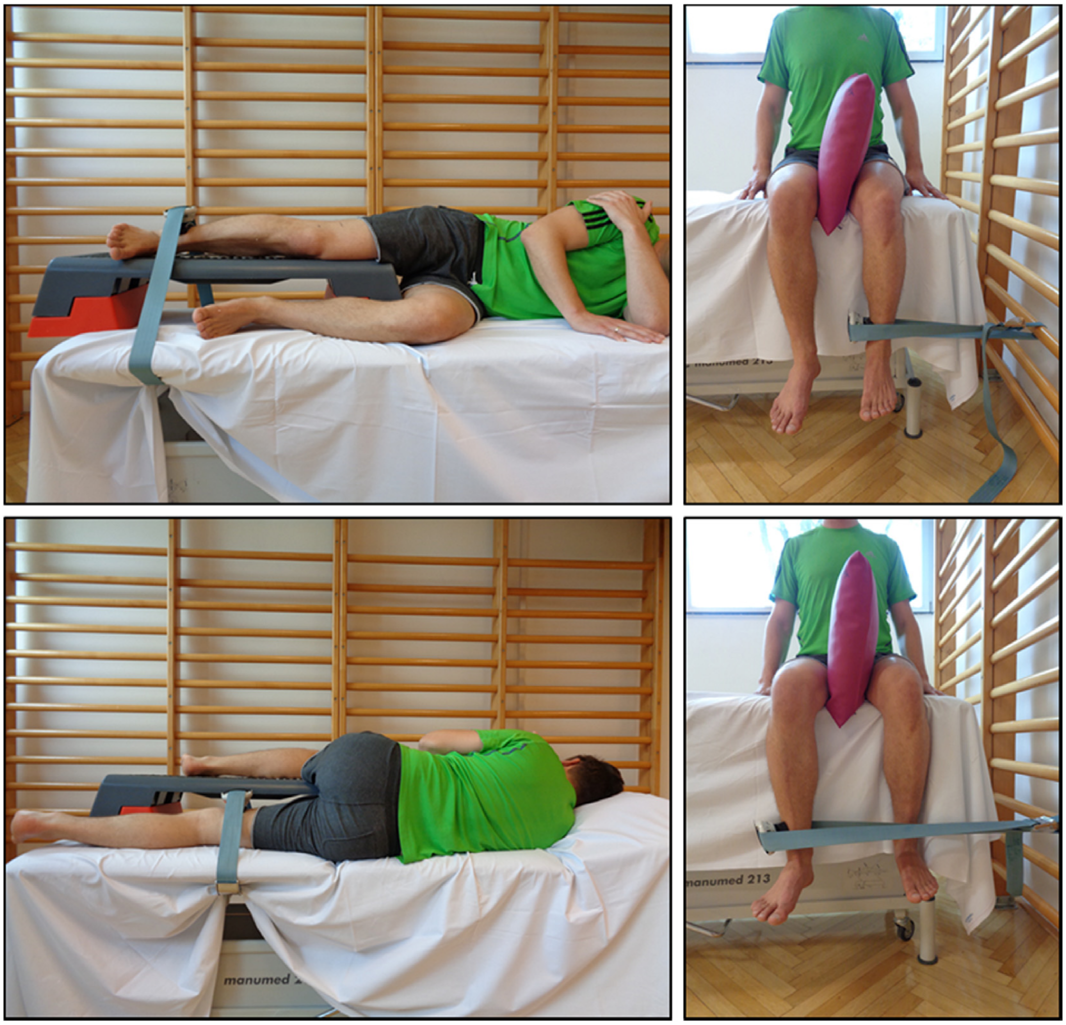

Fig. 2. Maximum voluntary contraction tests (abduction, external rotation, adduction, internal rotation) with stabilization strap.

Table 2
Descriptive characteristics of the study sample.

	ITBS (n = 14)	Control (n = 14)	*p*-value
Age (yr)	32.6 (6.6)	27.2 (6.6)	0.039
Height (m)	1.74 (0.09)	1.73 (0.1)	0.689
Mass (kg)	68.7 (10.2)	69.6 (13.4)	0.845
Body mass index	22.5 (2.0)	23.1 (2.4)	0.440
Sex (female, male)	7/7	7/7	
Duration of symptoms, median (IQR)	12.5 (29)	–	<0.001
Symptomatic limb	Right, 8; left, 9	–	
Dominant limb	Right, 13; left, 1	Right, 12; left, 2	
Pain severity (0–100)[a]			
At Rest	12.9 (14.4)	0	<0.001
Running	78.3 (14.6)	0	<0.001

Data are presented as mean (SD) unless otherwise stated.
[a] Measured using a 100 mm visual analog scale, where 0 indicates no pain and 100 indicates the worst imaginable pain.

After the training program, strength in the affected legs (Table 4) was significantly increased in hip ER ($t(16) = -2.56$, $p = 0.021$, $r = 0.54$), IR ($t(16) = -3.03$, $p = 0.008$, $r = 0.60$) and ADD ($t(16) = -3.55$, $p = 0.003$, $r = 0.66$) but not ABD ($t(16) = -0.66$, $p = 0.522$). Strength changes in the non-affected legs were non-significant (ER: $t(9) = -1.30$, $p = 0.226$; IR: $t(9) = -0.98$, $p = 0.353$; ABD: $t(9) = -0.11$, $p = 0.915$; ADD: $t(9) = -0.31$, $p = 0.764$).

4. Discussion

The purpose of the present study was to investigate whether the etiology of ITBS was associated with excessive ITB stiffness as well as weakness of hip muscles. Moreover, we aimed to test the effectiveness of a 6-week training therapy program in alleviating symptoms and reducing ITB stiffness. For these purposes, we assessed SWE propagation velocities, indicative of tissue stiffness,

Table 3
Baseline values of maximum isometric strength normalized to body mass.

	ITBS (N/kg)	CO (N/kg)	Difference (percent)
ER na/dom	1.88 ± 0.48	2.25 ± 0.43	19.68%
IR na/dom	2.08 ± 0.52	2.59 ± 0.51	24.52%
ABD na/dom	1.95 ± 0.65	2.61 ± 0.62	33.85%
ADD na/dom	3.84 ± 1.00	4.81 ± 1.03	25.26%
ER aff/nd	1.68 ± 0.39	2.32 ± 0.43	38.10%
IR aff/nd	2.07 ± 0.45	2.64 ± 0.64	27.54%
ABD aff/nd	1.93 ± 0.59	2.71 ± 0.78	40.41%
ADD aff/nd	3.74 ± 0.96	4.67 ± 1.01	24.87%

Data are presented as mean (SD). ITBS= Intervention group, CO= Control group, ER = external rotation, IR = internal rotation, ABD = abduction, ADD = adduction, na/dom = non affected/dominant leg, aff/nd = affected/non dominant leg.

Table 4
Treatment-associated changes in MVC muscle strength in the ITBS-affected legs (n = 17).

Direction	Baseline (N/kg)	Post-intervention (N/kg)	Change (%)	p-Value
ER	1.68 ± 0.39	1.99 ± 0.36	18.5%	0.021
IR	2.07 ± 0.45	2.43 ± 0.41	17.4%	0.008
ABD	1.93 ± 0.59	2.06 ± 0.56	6.7%	0.522
ADD	3.74 ± 0.96	4.45 ± 1.16	19.0%	0.003

ER = external rotation, IR = internal rotation, ABD = abduction, ADD = adduction.

and hip MVC strength in both patients suffering from ITBS and physically active, healthy control subjects. Conflicting with our hypothesis, our data showed that baseline ITB stiffness was not significantly increased in patients' affected legs. Six weeks of training therapy did not have a detonizing effect, but rather increased ITB stiffness by ~14%, while provoking significant improvements in the levels of pain and lower extremity function. Results further showed significant hip muscle weakness in ITBS patients that could not be fully corrected during 6 weeks of therapy.

The etiology of ITBS has been the subject of scientific debate for decades (Ellis et al., 2007; Fairclough et al., 2006; Orchard et al., 1996). The current hypothesis purports that ITBS is an impingement syndrome, in which cysts, bursae or highly innervated fat pads lying beneath the ITB in the area of the lateral femoral epicondyle are compressed, resulting in inflammation and associated symptoms (Cowden & Barber, 2014; Flato et al., 2017; Lui, 2015; Muhle et al., 1999). With this compression model in mind, the tension of the ITB becomes a critical factor, but technical difficulties have so far precluded *in vivo* measurements. In recent years, novel ultrasound-based elastography techniques, such as SWE, have started expanding into clinical routine. SWE relies on the emission of an acoustic radiation impulse to create perturbations in the examined tissue, the spreading of which is tracked by ultrafast imaging protocols. The velocity of the provoked shear wave is contingent upon the mechanical properties of the examined tissue and used to generate elastograms, i.e. quantitative maps of tissue stiffness (Gennisson et al., 2013; Sigrist et al., 2017). While the technique is most frequently used to investigate the mechanical properties of the human liver, recent years have seen significant advancements in the development of musculoskeletal applications of SWE (Ryu & Jeong, 2017). Studies performed in skeletal muscle (Dubois et al., 2015; Heales et al., 2018) and tendons (Heales et al., 2018; Hsiao et al., 2015) show promising results, and in a recent work by Tateuchi et al. (Tateuchi et al., 2015) excellent reliability of SWE measures has also been reported for the ITB. To our knowledge, our study is the first to apply SWE to study tissue stiffness in patients suffering from ITBS. Our own reliability analyses (not yet published) showed fair between-day reproducibility of measurements, with intraclass correlation coefficients and typical errors of measurement ranging from 0.54 (ITB) - 0.79 (TFL) and 0.81 (GM) - 1.44 (ITB) m/s, respectively.

Conflicting with the proposed compression model of pathogenesis, baseline measurements showed no increased ITB stiffness in patients' affected legs. On the contrary, the SWE propagation velocities measured in the TFL, a muscle responsible for tensioning the ITB, was even significantly lower in ITBS patients. One possible explanation for this observation is that in the presence of ITBS neural drive to the TFL is reduced, to lower its resting tension and, thus, keep ITB tone in a physiological range. In addition to the lack of baseline differences, we found a 6-week training therapy to result in a significant increase in the SWE propagation velocities measured in the distal ITB. Under consideration of the compression model, physiotherapeutic interventions typically aim to reduce ITB tone through stretching exercise (Cheatham et al., 2017; Junker & Stöggl, 2015; Maeda et al., 2017) or other myofascial interventions, such as foam rolling (Fredericson et al., 2000b; Taş et al., 2017; Tateuchi et al., 2015; Wilke et al., 2019). Thus, we hypothesized that ITB stiffness would be reduced after the intervention. It should be noted, however, that the training therapy also consisted of strengthening exercises targeting the hip-stabilizing muscles. While training-induced changes in TFL and GM propagation velocities were non-significant, it may be speculated that

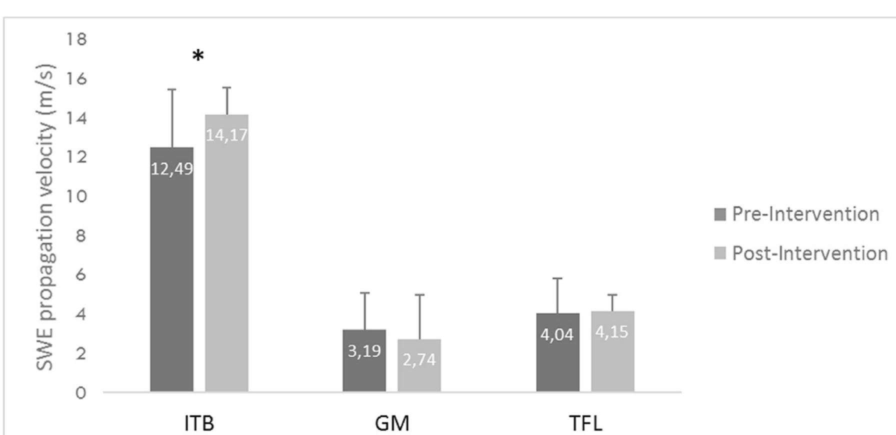

Fig. 3. Treatment effects on shear-wave propagation velocity in the affected legs compared pre- and post-intervention. Bars and error bars represent the means and standard deviations measured in the iliotibial band (ITB), gluteus maximus (GM) and tensor fasciae latae (TFL) muscles. Note the significant increase in shear-wave propagation velocity in the ITB after physiotherapy. *p < 0.05.

strength training would not only increase the maximal strength (discussed in the following paragraph) but also the resting tone of muscles inserting into the ITB. In consequence, strengthening exercises might counteract the effects of stretching and other detonizing techniques, resulting in an actual increase in ITB stiffness. Lacking surface EMG measures to substantiate possible differences or changes in muscle resting tones, however, these assumptions are highly speculative and warrant further investigation.

It is also interesting to note that, in spite of significant increases in ITB stiffness, symptoms were significantly improved after the training intervention. Self-reported levels of pain during running decreased from 78 to 17 on a 100-mm VAS (−78%), with 50% of patients reporting to be absolutely pain-free after physiotherapy. Moreover, LEFS scale measures increased by 11 points (+17%), reflecting a significant and clinically meaningful improvement in lower extremity function (Binkley et al., 1999). In the absence of decreases in ITB tone to provide a biomechanical rationale for the improvement of symptoms, it may be speculated that inflammatory processes affecting the lateral knee receded in response to prolonged abstinence from running.

Another aim of this study was to comprehensively measure hip muscle strength in ITBS patients for comparison with non-affected legs and healthy control subjects. Consistent with our hypothesis, the ITBS group showed significantly lower MVC values in hip abduction (−40% with respect to healthy controls) and external rotation (−38%). It must be noted that the ITBS patients were on average 5.4 years older than control subjects. While muscle strength typically reaches its peak in the early 20s, it plateaus until the late 30s, and age-associated losses in muscle strength (if at all existent) between the ages of 27 years (control group) and 33 years (ITBS group) would be of negligible dimension (Ferrucci et al., 2012; Larsson et al., 1979; Lindle et al., 1997). Hence, they could not fully account for the between-group differences observed in this study. Our findings are in agreement with earlier studies reporting hip abductor and external rotator weakness as well as excessive hip adduction and internal rotation during stance (Chuter & Janse de Jonge, 2012; Fredericson et al., 2000a; Kollock et al., 2016; Noehren et al., 2014). It is assumed that these movements would elongate the ITB, thus increasing its tensile strain. It should be noted, however, that evidence regarding hip muscle strength in ITBS patients is not unequivocal, with several studies failing to find significant weakness of hip abductors or external rotators (Brown et al., 2019; Grau et al., 2008; Messier et al., 2018). In addition to the hip abductor and external rotator muscles, our study is the first to additionally assess the muscle strength of hip adductor and internal rotator muscles. Our results showed that strength deficits also concerned these muscle groups (adduction −25%, internal rotation −28%), without statistical differences between affected and non-affected legs. Jointly, these results suggest that subjects suffering from ITBS are likely to present with general hip muscle weakness. These strength deficits can be well addressed by physical training, which led to significant increases in MVC strength in all muscle groups (+17−19%), except the hip abductors (+7%, n. s.). The training-induced strength gains notwithstanding, however, strength levels remained well below those seen in the healthy control group, with differences of 24−25% persisting in both hip ad- and abduction.

This study is subject to a number of limitations. First and foremost, potential inaccuracies of the SWE technique need to be mentioned. A previous study by Tateuchi and colleagues (Tateuchi et al., 2015) reported excellent test-retest reproducibility of SWE measures obtained in the ITB, yet our own reliability assessments suggest that typical errors of measurement were 1.44 m/s, equivalent to approximately 11% of the mean propagation velocities measured in the ITB. Hence, smaller differences between groups or legs might have been missed. While care was taken to standardize subject positioning and measurement sites, further methodological refinements may be necessary to improve the accuracy of SWE measurements obtained in the ITB. One specific problem relates to the possibility of saturation effects. While live visual inspection of images during examination revealed no indication of such artifacts in our study, it cannot be ruled out that in some subjects the values of individual pixels might exceed the upper end of the elastic scale and would, consequently, be clipped off at 600 kPa. Moreover, ITB measurements were only obtained in the unloaded condition and at a single site, near the lateral femoral epicondyle (i.e., the site where symptoms typically occur). Further research is required to examine whether measurement results would be affected by weight-bearing, knee and hip joint angle or the proximo-distal measurement position. In addition to methodological challenges, it must be pointed out that our study included only patients with pre-existent ITBS. Hence, it is not known whether the observed differences in muscle strength are causal for the pathogenesis of ITBS or rather a consequence of symptoms. Only prospective studies may establish cause-and-effect relationships. The subjects in the ITBS group were approximately five years older than controls, which might have affected our results and, particularly, the strength measurements. As explained in the Discussion, however, we expect age-associated bias (if at all present) to be very minor. Moreover, our sample comprised 50% both men and women. While sex differences in the tissue biomechanical properties cannot be ruled out, a recent study reported no effect of gender on the iliotibial band stiffness as measured in a neutral knee joint position (Kim et al., 2020). As regards muscle strength, only MVC measures are reported in this paper. Since ITBS symptoms typically occur after a certain time of running, measures of muscular endurance might be more informative. In fact, muscle endurance tests consisting of 30 maximal, consecutive contractions were included into the acquisition protocol, but the reliability of these measures was inadequate, so data were not reported. Finally, our study included 14 ITBS patients and an equal number of healthy control subjects. Due to bilateral afflictions only 10 non-affected legs could be studied in this sample, which limits statistical power.

5. Conclusion

In conclusion, this study represents the first attempt to assess the stiffness of the ITB and in-series muscles through the innovative, ultrasound-based SWE technique in patients suffering from ITBS. Our results showed no differences in baseline ITB stiffness between patients and healthy control subjects. In the TFL, which acts to tension the ITB, stiffness was even significantly higher in healthy control subjects. These findings challenge the notion that excessive ITB tension was the primary causative factor for the pathogenesis of ITBS. A 6-week physiotherapeutic intervention, consisting of exercises aimed at strengthening the hip muscles and detonizing the ITB, led to significant increases in muscle strength and reduction of symptoms, in spite of a 14% increase in ITB stiffness. Future studies to be performed in our laboratory will examine the regional heterogeneity and activity-dependence of ITB stiffness.

Ethical approval

The study was approved by the Ethics Committee of the Medical University of Innsbruck (1090/2018).

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Ethical statement

The study was approved by the Ethics Committee of the Medical University of Innsbruck (1090/2018) and subjects gave their informed consent.

Declaration of competing interest

Declarations of interest: none.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2020.06.015.

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