A three-experiment examination of iliotibial band strain characteristics during different conditions using musculoskeletal simulation.

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Abstract

PURPOSE: Iliotibial band syndrome (ITBS) is a common chronic pathology mediated via excessive Iliotibial band (ITB) strain. The purpose using a three-experiment approach is to provide insight into the differences in strain between different athletic movements, the incidence of ITBS in females, the efficacy of different prophylactic modalities for ITBS and also the kinematic parameters associated with ITB strain.

METHODS: Experiment 1 examined male and female athletes performing run, 45° cut and one-legged hop movements, experiment 2 observed males and females, whilst running in five different orthotic conditions and experiment 3 examined males and females riding a cycle ergometer at 70, 80 and 90RPM whilst in prophylactic knee brace and no-brace conditions. In each experiment, kinematics were obtained using a motion capture system and ITB strain was measured using a musculoskeletal simulation approach.

RESULTS: In experiment 1 ITB strain was greater in the run (male=3.87% & female=4.37%; P<0.001) and cut (male=3.12% & female=4.06%; P<0.001) movements compared to hop (male=0.87% & female=1.54%). Experiment 2 showed that females exhibited increased ITB strain (male=6.34% & female=8.91%; P<0.05) and ITB strain velocity (male=57.17%/s & female=77.41%/s; P<0.05) and also in females that ITB strain velocity was greater (P≤0.01) in lateral (80.22%/s) and no-orthotic (83.01%/s) conditions compared to medial (72.58%/s) and off the shelf orthoses (74.52%/s). The regression analyses across movements showed that ITB strain was predicted by sagittal and coronal plane mechanics at the hip (R^2=0.15-0.30; P<0.05) and sagittal, coronal and transverse plane kinematics at the knee joint (R^2=0.15-0.22; P<0.05).

CONCLUSION: Further insight is provided into differences in ITB strain across functional athletic movements, the increased incidence of ITBS in females and the parameters linked most strongly with ITB strain during different movements is provided; whilst also highlighting the prophylactic efficacy of medial and off the shelf orthoses in female runners.

Introduction

Iliotibial band syndrome (ITBS) presents clinically as inflammation and at the distal aspect of the iliotibial band (ITB) (1) and is twice as likely to develop in females in relation to age matched males (2, 3). ITBS is second only to patellofemoral pain in terms of the most common chronic pathologies, accounting for up to 12% of all running-related injuries (3). In addition, ITBS is also a common chronic complaint in cyclists, responsible for 15% of all chronic knee pathologies (4). Finally, Devan et al. showed that ITBS was the most common pathology in field hockey, soccer, and basketball; sporting disciplines characterized by more dynamic high impact actions such as jumping, single limb landings/hopping and cutting movements (5). Concerningly, ITBS habitually causes athletes to reduce engagement with sport and physical activity (6), and frequently leads to associated psychological disorders (7).

Importantly, prospective analyses have shown both ITB strain and strain rate to be the primary factors in the development of ITBS (8). However, the biomechanical factors that cause ITB strain are not well understood. Several investigations have examined the three-dimensional kinematics linked to the aetiology of ITBS; with hip adduction, internal and external rotation, alongside flexion, adduction, ankle eversion and tibial internal rotation, considered to cause strain at the ITB (8, 10). Importantly, Hamill et al. also proposed an impingement zone present between 20-30° of knee flexion due to the interaction between the distal fibers of the ITB and lateral femoral epicondyle (8). Prevention programmes have had limited success in attenuating the rate of ITBS (10). However, the efficacy of any intervention is dependent on a sound comprehension of the causative mechanisms of the associated condition. Currently, the biomechanical factors that mediate ITB strain are not well established. However, advances in musculoskeletal simulation techniques now allow indices of ITB strain and strain rate to be obtained. Therefore, the predictive effects of the three-dimensional kinematic parameters that contribute to ITB strain parameters can now be explored, which will be of practical and clinical relevance.

Because of the high incidence of ITBS, prophylactic strategies are a key priority for clinical research. Foot orthoses are frequently adopted for the prevention and treatment of running injuries, and a range of orthoses are available (11). Only one investigation has examined the effects of orthoses on ITB strain mechanics, with Day et al. showing that neither 7° lateral, 3° lateral, 3° medial or 7° medial wedged orthoses significantly influenced ITB strain (12). However, there are a variety of commercially available orthoses; typically classified as off-the-shelf, wedged or semi-custom devices, and there has not been any investigation regarding the influence of different orthotic devices on ITB strain characteristics (11). Similarly, prophylactic knee braces are also frequently used across a range of athletic disciplines to attenuate the factors linked to the aetiology of injury. Prophylactic braces are frequently utilized during many of the sporting activities associated with ITBS, yet there have not been any investigations examining their effects on ITB strain parameters (13). Therefore, it is clear that further investigation of these prophylactic modalities is required, which may provide important clinical information for the prevention of ITBS across different athletic activities.

Though females are at increased risk from ITBS, the biomechanical mechanisms responsible for the augmented incidence of ITBS are not well understood (3). Prospective analyses show that females with ITBS are associated with enhanced hip external rotation, knee internal rotation and hip adduction, whereas males were associated with greater ankle eversion compared to healthy counterparts (9; 14). Importantly, Day et al. showed that females exhibited increased ITB strain and strain rate during running, although it is unknown whether females exhibit enhanced ITB mechanics in other disciplines/movements commonly associated with ITBS such as cycling, single limb landings and cutting (12). There is a clear need to further investigate the mechanics of the ITB in females across a range of athletic movements commonly associated with ITBS, in order to gain further insight into the increased incidence of this pathology in female athletes.

The aims of the current investigation by using a three-experiment musculoskeletal simulation-based approach were to investigate: 1. the effects of different functional sports movements on ITB strain characteristics in both male and female athletes, 2. the effects of different orthotic conditions on ITB strain characteristics during running in both male and female runners, 3. the effects of prophylactic knee bracing on ITB strain characteristics during cycling at different intensities using both males and female cyclists and 4. the three-dimensional kinematic parameters most strongly associated with ITB strain during different movements commonly associated with ITBS.

In relation to the aforementioned aims, the current investigation tests the following hypotheses; 1. hop and cut movements will be associated with increased ITB strain characteristics compared to running; 2. across all of the examined movements females will exhibit greater ITB strain characteristics compared to males; 3. wedged orthoses will reduce ITB strain characteristics compared to running with no orthoses, 4. prophylactic knee bracing will reduce ITB strain characteristics during cycling and 5. ITB strain will most strongly be predicted by coronal and transverse plane kinematics at the hip and knee joints.

Methods

For each of the three investigations, participants provided written informed consent and ethical approval was obtained from the University of Central Lancashire, in accordance with the principles documented in the Declaration of Helsinki. All participants were free from lower extremity musculoskeletal pathology at the time of data collection and had not undergone surgical intervention at the knee joint.

Experiment 1

Participants

Fifteen male (age 30.1 ± 5.2 years, height 1.75 ± 0.07 m and body mass 77.1 ± 10.8 kg) and fifteen female (age 29.6 ± 5.6 years, height 1.66 ± 0.06 m and body mass 65.8 ± 9.9 kg) recreational athletes volunteered to take part in the current investigation.

Procedure

Participants completed five trials of three sport-specific movements, (run, one legged hop and 45° cut) and the order in which participants performed each movement was counterbalanced. To ensure consistency, each participant wore the same footwear (Asics, Patriot 6). Kinematic information was obtained using an eight-camera motion capture system (Qualisys Medical AB, Goteburg, Sweden) with a capture frequency of 250 Hz. To measure ground reaction forces (GRF), an embedded piezoelectric force platform (Kistler National Instruments, Model 9281CA) operating at 1000 Hz was adopted. The GRF and kinematic information were synchronously obtained and interfaced using Qualisys track manager.

To define the anatomical frames of the thorax, pelvis, thighs, shanks and feet, passive retroreflective markers of 19mm diameter were placed at the C7, T12 and xiphoid process landmarks and also positioned bilaterally onto the acromion process, iliac crest, anterior superior iliac spine (ASIS), posterior super iliac spine (PSIS), medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanter, calcaneus, first metatarsal and fifth metatarsal. The hip, knee and ankle joint centre's were delineated according to previously established guidelines (15-17). Carbon-fibre tracking clusters comprising of four non-linear retroreflective markers were positioned onto the thigh and shank segments. The foot segments were tracked via the calcaneus, first and fifth metatarsal, the pelvic segment using the PSIS and ASIS markers and the thorax via the T12, C7 and xiphoid markers. Static calibration trials were obtained with the participant in the anatomical position in order for the positions of the anatomical markers to be referenced in relation to the tracking clusters/markers, following which those not required for dynamic data were removed. The Z (transverse) axis was oriented vertically from the distal segment end to the proximal segment end. The Y (coronal) axis was oriented in the segment from posterior to anterior. Finally, the X (sagittal) axis orientation was determined using the right-hand rule and was oriented from medial to lateral.

Data were collected during the cut and hop movements according to below procedures:

Run

Participants ran at 4.0 ± 0.2 m/s and struck the force platform with their right (dominant) limb. The average velocity of running was monitored using infra-red timing gates (SmartSpeed Ltd UK), and the stance phase of running was defined as the duration over > 20 N of vertical force was applied to the force platform.

Cut

Participants completed 45° sideways cut movements using an approach velocity of 4.0 ± 0.2 m/s striking the force platform with their right (dominant) limb. Cut angles were measured from the centre of the force plate and the corresponding line of movement was delineated using masking tape so that it was clearly evident to participants. The stance phase of the cut movement was defined as the duration over > 20 N of vertical force applied to the force platform.

Hop

Participants began standing by on their dominant limb, they were then requested to hop forward maximally, landing on the force platform with same leg without losing balance. The arms were held across the chest to remove arm-swing contribution. The hop movement was defined as the duration from foot contact (defined as > 20 N of vertical force applied to the force platform) to maximum knee flexion. The hop distance for each participant was established during practice trials, and the starting position was marked using masking tape.

Processing

Dynamic trials were digitized using Qualisys Track Manager (Qualisys Medical AB, Goteburg, Sweden) in order to identify anatomical and tracking markers then exported as C3D files to Visual 3D (C-Motion, Germantown, MD, USA). Marker trajectories were smoothed with a cut-off frequency of 12 Hz respectively, using a low-pass Butterworth 4th order zero lag filter.

Within Visual 3D kinematics of the hip, knee, ankle and tibia were quantified using an XYZ cardan sequence of rotations (where X is flexion-extension; Y is ab-adduction and is Z is internal-external rotation). Taking into account the kinematic risk factors linked to the aetiology of ITBS, three-dimensional angular kinematic measures that were extracted for statistical analysis were peak ankle dorsiflexion and eversion; knee flexion, abduction, and internal rotation; hip flexion, adduction/ abduction, and internal rotation. In addition, peak tibial internal rotation was quantified as a function of tibial co-ordinate system in relation to the foot co-ordinate axes, in accordance with previous work (18). Furthermore, the angular range of motion (ROM) from footstrike to the peak angle for each of the aforementioned parameters were also extracted. In addition, from the knee kinematic information, the duration of impingement was defined as the absolute duration (ms) in which the knee flexion angles were between 20-30° i.e. the period during which the ITB is considered to interacted with the lateral femoral epicondyle (8). Finally, the relative duration of impingement (%) was calculated by dividing the absolute duration of impingement by the total duration of each movement and multiplying by 100.

Following this, data during the appropriate phases of each movement were exported from Visual 3D into OpenSim 3.3 software (Simtk.org). A validated musculoskeletal model was firstly scaled to account for the anthropometrics of each participant. This model had twelve segments, 23 degrees of freedom and 92 muscle-tendon actuators and was adapted from the generic OpenSim gait2392 model to include the ITB (19). The ITB itself was included within the gait2392 model but as a muscle with only a passive contractile component and an optimal muscle fiber length of zero (19). This model has been adopted previously to successfully resolve differences in ITB strain between footwear, footstrikes, orthoses, sex and between those with and without ITBS (8, 12, 20).

ITB kinematics during each movement were calculated via the muscle analyses function within OpenSim. Peak ITB strain (%) was calculated by dividing the change in length of the IT band during each movement by its resting length then multiplying by 100 to create a percentage. In addition, the peak strain rate (%/s) was calculated as the maximum change in strain between adjacent data points using a first derivative function.

Statistical analyses

Differences were examined using 3 (movement) x 2 (sex) mixed ANOVAs. Post-hoc pairwise comparisons (with Bonferroni adjustments) were adopted in the event of a significant main effect and % differences were also presented for all statistical differences. In addition, linear regression analyses were adopted to determine the biomechanical variables that significantly predicted the peak ITB strain for each movement. Effect sizes for comparative analyses were calculated using partial Eta^2 ($p\eta^2$) and for regression analyses using R^2. Statistical actions were conducted using SPSS v25.0 (SPSS Inc., Chicago, USA), with statistical significance was accepted at the $P \leq 0.05$ level.

Experiment 2

Participants

Sixteen male (age 28.7 ± 6.1 years, height 1.78 ± 0.05 m, body mass 76.6 ± 8.7 kg) and twenty females (age 32.3 ± 7.4 years, height 1.61 ± 0.06 m, body mass 65.5 ± 7.3 kg) volunteered to take part in the current investigation. All were recreational runners who trained 3 times/week, completing a minimum of 35 km.

Orthoses

Five experimental conditions were examined in this investigation (lateral, medial, semi-custom, off the shelf and no orthotic). For the medial and lateral orthoses, commercially available full-length orthoses with 5° medial and lateral wedges (Slimflex Simple, High Density, Full Length, Algeos UK) were examined. The semi-custom insoles (Sole Control, Sole, Milton Keynes, UK) were moulded by placing them into a pre-heated oven (90 °C) for a duration of two minutes in accordance with the manufacturers instructions. For the off the shelf orthoses, commercially available shock absorbing insoles were utilized (Sorbothane, shock stopper sorbo Pro, Nottinghamshire, UK). Each participant wore the same footwear (Asics, Patriot 6).

Procedure

Kinematic information was obtained using the procedure and biomechanical modelling approach outlined for running in experiment 1.

Processing

The same processing techniques as experiment 1 were adopted and the duration of impingement, relative duration of impingement, peak ITB strain, peak ITB strain velocity, peak angles and angular ROM's during the stance phase were extracted for each experimental condition.

Statistical analyses

Differences were examined using 5 (orthoses) x 2 (sex) mixed ANOVAs. The same statistical principles and reporting as experiment 1 were adhered to.

Experiment 3

Participants

Twelve male (age 28.1 ± 6.3 years, height 1.77 ± 0.07 m and body mass 79.0 ± 9.3 kg) and twelve female (age 26.7 ± 5.7 years, height 1.64 ± 0.06 m and body mass 62.6 ± 7.3 kg) recreational volunteered to take part in this study. All had at least 2 years of road cycling experience.

Knee brace

A single nylon/silicone knee brace was utilized in this investigation (Kuangmi 1 PC compression knee sleeve), which was worn on the dominant (right) limb in all participants. The brace examined as part of this study, is a lightweight knee joint compression sleeve designed to provide support and enhance joint proprioception.

Procedure

Kinematic information was obtained using the procedure outlined in experiment 1. Participants rode a stationary ergometer SRM 'Indoor Trainer' (SRM, Schoberer, Germany) for 6 minutes at fixed cadences of 70, 80 and 90 RPM in both brace and no-sleeve conditions. The experimental conditions were completed in a counterbalanced order and a standardized rest period of 5 minutes was allowed between trials. The bicycle set-up was conducted in accordance with previous recommendations and maintained between each condition. The cycling shoes and cleats were also maintained across all trials (21).

The same biomechanical modelling approach as experiment 1 was utilized and five pedal cycles were examined in each condition during minutes 2-3. The pedal cycle was delineated using concurrent instances in which the right pedal was positioned at top dead centre, in accordance with Sinclair et al. (21).

Processing

The same processing techniques as experiment 1 were adopted and the duration of impingement, relative duration of impingement, peak ITB strain, peak ITB strain velocity, peak angles and angular ROM's during the pedal cycle were extracted for each experimental condition.

Statistical analyses

Differences were examined using 3 (cadence) x 2 (knee brace) x 2 (sex) mixed ANOVAs and linear regression analyses were adopted to determine the biomechanical variables that significantly predicted peak ITB strain during the pedal cycle. The same statistical principles and reporting as experiment 1 were adhered to.

Results

Experiment 1

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For the duration of impingement there was a main effect for movement ($P<0.001$, $P\eta^2 = 0.22$). Pairwise comparisons showed that the impingement duration was greater in the run compared to the cut ($P<0.001$, % difference = 23.0%) and hop ($P<0.001$, % difference = 25.8%) movements (Table 1). For the relative duration of impingement there was a main effect for movement ($P<0.001$, $P\eta^2 = 0.25$). Pairwise comparisons showed that the relative impingement duration was greater in the run compared to the cut ($P<0.001$, % difference = 36.4%) and in the hop compared to the cut ($P<0.001$, % difference = 30.8%) movement (Table 1). For the peak ITB strain there was a main effect for movement ($P<0.001$, $P\eta^2 = 0.52$). Pairwise comparisons showed that peak strain was greater in the run ($P<0.001$, % difference = 109.4%) and cut ($P<0.001$, % difference = 99.4%) compared to the hop (Table 1). For the peak ITB strain velocity there was a main effect for movement ($P<0.001$, $P\eta^2 = 0.29$). Pairwise comparisons showed that peak strain velocity was greater in the run ($P<0.001$, % difference = 52.7%) and cut ($P<0.001$, % difference = 59.4%) compared to the hop (Table 1). For the run movement, the regression analyses showed that peak ITB strain was a significantly predicted by peak hip flexion (Figure 1a), peak knee flexion (Figure 1b) and peak hip adduction (Figure 1c). In addition, for the cut movement, the regression analyses showed that peak ITB strain was a significantly predicted by sagittal hip ROM (Figure 1d), sagittal knee ROM (Figure 1e) and coronal hip ROM (Figure 1f). Finally, for the hop movement the regression analyses showed that peak ITB strain was a significantly predicted by sagittal hip ROM (Figure 1g) and peak hip abduction (Figure 1h).

Experiment 2

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For the peak ITB strain there was a main effect for sex ($P<0.05$, $P\eta^2 = 0.17$), indicating that peak strain was greater in females (% difference = 33.8%) (Table 2). In addition, for the peak ITB strain velocity there was a main effect for sex ($P<0.05$, $P\eta^2 = 0.13$), indicating that peak strain velocity was greater in females (% difference = 30.1%) (Table 2). There was also a sex*orthoses interaction ($P<0.05$, $P\eta^2 = 0.14$). Simple main effects showed that there was main effect for orthoses for females ($P<0.05$, $P\eta^2 = 0.18$) but no main effect for orthoses in males ($P>0.05$, $P\eta^2 = 0.05$). Pairwise comparisons showed that in females, peak strain velocity was greater in the lateral orthoses compared to medial ($P<0.001$, % difference = 10.0%) and off the shelf orthoses ($P=0.008$, % difference = 7.4%) and also in the no-orthotic compared to medial ($P=0.04$, % difference = 13.4%) and off the shelf orthoses ($P=0.03$, % difference = 10.8%) (Table 2).

Experiment 3

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For the peak ITB strain velocity there was a main effect for cadence ($P<0.001$, $P\eta^2 = 0.78$). Pairwise comparisons showed that peak strain velocity was greater at 90RPM compared to the 80RPM ($P<0.001$, % difference = 9.6%) and 70RPM ($P<0.001$, % difference = 22.3%) conditions and at 80RPM ($P<0.001$, % difference = 12.8%) compared to 70RPM (Table 3). The regression analyses showed that peak ITB strain was a significantly predicted by peak hip flexion (Figure 2a), peak hip abduction (Figure 2b), sagittal hip ROM (Figure 2c) and transverse knee ROM (Figure 2d).

Discussion

The current investigation using a three-experiment approach represents the first study to explore differences in ITB strain parameters between movements, males and females, different orthoses and knee braces as well as investigating the kinematic parameters most strongly associated with ITB strain. A study of this nature may provide further insight into the differences in ITB strain parameters between different athletic movements, the increased incidence of ITBS in female athletes, the potential efficacy of different prophylactic modalities for the prevention ITBS as well as the three-dimensional kinematic parameters that most strongly predict ITB strain across different sports movements.

The most important finding from experiment 1 is that peak ITB strain and strain velocity alongside the impingement duration were greatest in the run and cut movements compared to the hop. This observation does not support hypothesis 1 yet may be clinically meaningful as the aetiology of ITBS is considered to be mediated through enhanced impingement/ITB strain characteristics (8). Experiment 1 therefore indicates that the biomechanical mechanisms responsible for the initiation and progression of ITBS are greater in the run and cut movements. However, taking into account the cyclic nature of running whereby over 1000 footfalls are required per mile, experiment 1 also provides insight into the high incidence of ITBS in runners (3, 22). Furthermore, the observations from experiment 3 indicate that ITB strain velocity was augmented linearly alongside increases in cycling cadence. Therefore, experiment 3 indicates that, at increased intensities, the risk from the mechanical parameters linked to the aetiology of ITBS is enhanced during cycling.

Females are at a 2-fold increased risk of ITBS; yet the aetiology of this sex discrepancy is not well understood. The findings from experiments 1 and 3 did not support hypothesis 2 and showed that there were no significant differences between males and females (3). However, in support of hypothesis 2 and experiment 2 importantly showed that ITB strain characteristics during running were significantly larger in females. As ITBS is believed to initiate when the ITB experiences excessive strain (8), the findings from experiment 2 indicate that the increased risk of ITBS in females may be movement dependent. Nonetheless, given the statistical differences amongst sexes during running this experiment 2 provides insight into the increased incidence of ITBS females.

Experiments 2 and 3 were designed to provide further insight into the prophylactic efficacy of foot orthoses and knee braces during different movements commonly associated with ITBS (3; 4). The observations from experiment 3 did not support hypothesis 4 and importantly showed that prophylactic knee bracing did not significantly influence ITB strain characteristics during the pedal cycle. Therefore, whilst Sinclair et al. showed that knee bracing attenuated patellofemoral joint stress linked to the aetiology of patellofemoral pain during cycling, it appears that bracing may not be effective in attenuating ITB strain (22). Furthermore, the findings from experiment 2 partially support hypothesis 3 and also those of Day et al. in that foot orthoses did not influence ITB strain characteristics in male runners. However, in females ITB strain velocity was greater in the lateral and no-orthotic conditions compared to the off the shelf and medial orthoses (12). As ITB strain velocity is linked prospectively to the aetiology of ITBS, experiment 2 indicates that running with medial and off the shelf orthoses may be preferable over the lateral wedge and no-orthotic conditions to reduce the biomechanical parameters linked to ITBS during running (8).

In partial support of hypothesis 5, the regression analyses conducted as part of experiments 1 and 3 importantly showed that peak strain was predicted by sagittal and coronal plane angular parameters at the hip in addition to sagittal, coronal and transverse plane parameters at the knee joint. Proximally, the ITB originates at the fascial components of the gluteus maximus and attaches distally at Gerdy's tubercle on the anterolateral aspect of the tibia (1). Therefore, the findings from experiments 1 and 3 appear logical and support the findings from Hamill et al. in terms of the parameters considered to elongate the ITB (8). However, although Phinyomark et al. showed that males with ITBS exhibit increased ankle eversion; experiments 1 and 3 do not support this as ankle eversion/ tibial internal rotation characteristics were not associated with ITB strain (9). The efficacy of any prophylactic or treatment intervention modality is reliant upon a clear understanding of the underlying mechanisms linked to the aetiology of the associated condition (24). Therefore, the observations provided from experiments 1 and 3 provide insight into the kinematic parameters that future effective treatment modalities should seek to attenuate. However, it should noted that the R^2 values provided from the regression analyses were relatively small, indicating that further investigation of additional biomechanical parameters is required if we are to fully understand the mechanical factors that cause strain at the ITB.

Limitations

A potential limitation is that the kinematics driven musculoskeletal simulation model adopted to quantify ITB mechanics was not able to provide a direct measure of ITB friction or account for the inter-variability in the ITB construction (12). It should be noted that direct measures are not possible and that the magnitudes of ITB strain are consistent with those presented in the scientific literature for in-vivo strain and lower than the failure point shown through cadaver analyses (25). Nonetheless, there is considerable scope for future development of simulation-based models to address and improve upon these limitations; in order to provide more accurate and valid musculoskeletal simulations of ITB mechanics linked to the aetiology of ITBS.

Conclusion

The findings from the current three-experiment investigation provide further insight into differences in ITB strain parameters across functional athletic movements, the mechanisms responsible for the increased incidence of ITBS in females and the kinematic parameters linked most strongly with ITB strain during different movements, whilst also highlighting the prophylactic efficacy of medial and off the shelf orthoses in attenuating the mechanisms linked to the aetiology of ITBS in female runners.

References

1. Fairclough, J., Hayashi, K., Toumi, H., Lyons, K., Bydder, G., Phillips, N., Benjamin, M. (2006). The functional anatomy of the Iliotibial band during flexion and extension of the knee: implications for understanding Iliotibial band syndrome. Journal of Anatomy, 208(3), 309-316.
2. Fredericson, M., Wolf, C. (2005). Iliotibial band syndrome in runners. Sports Medicine, 35(5), 451-459.
3. Taunton, J. E., Ryan, M. B., Clement, D. B., McKenzie, D. C., Lloyd-Smith, D. R., Zumbo, B. D. (2002). A retrospective case-control analysis of 2002 running injuries. British Journal of Sports Medicine, 36(2), 95-101.
4. Holmes, J. C., Pruitt, A. L., Whalen, N. J. (1993). Iliotibial band syndrome in cyclists. The American Journal of Sports Medicine, 21(3), 419-424.
5. Devan, M. R., Pescatello, L. S., Faghri, P., Anderson, J. (2004). A prospective study of overuse knee injuries among female athletes with muscle imbalances and structural abnormalities. Journal of Athletic Training, 39(3), 263-267.
6. Shamus, J., Shamus, E. (2015). The management of Iliotibial band syndrome with a multifaceted approach: a double case report. International Journal of Sports Physical Therapy, 10(3), 378-390.
7. Yang, J., Schaefer, J. T., Zhang, N., Covassin, T., Ding, K., Heiden, E. (2014). Social support from the athletic trainer and symptoms of depression and anxiety at return to play. Journal of Athletic Training, 49(6), 773-779.
8. Hamill, J., Miller, R., Noehren, B., Davis, I. (2008). A prospective study of Iliotibial band strain in runners. Clinical Biomechanics, 23(8), 1018-1025.
9. Phinyomark, A., Osis, S., Hettinga, B. A., Leigh, R., Ferber, R. (2015). Gender differences in gait kinematics in runners with iliotibial band syndrome. Scandinavian Journal of Medicine & Science in Sports, 25(6), 744-753.

10. Ramsey, C.A. (2016). Running from Iliotibial Band Syndrome: A Guide for Preventing Overuse Injuries. Strategies, 29(2), 27-33.
11. Sinclair, J., Ingram, J., Taylor, P. J., Chockalingam, N. (2019). Acute effects of different orthoses on lower extremity kinetics and kinematics during running; a musculoskeletal simulation analysis. Acta of Bioengineering and Biomechanics (In press).
12. Day, E. M., Gillette, J. C. (2019). Acute Effects of Wedge Orthoses and Sex on Iliotibial Band Strain During Overground Running in Nonfatiguing Conditions. Journal of Orthopaedic & Sports Physical Therapy, 49(10), 743-750.
13. Sinclair, J., Vincent, H., Richards, J. D. (2017). Effects of prophylactic knee bracing on knee joint kinetics and kinematics during netball specific movements. Physical Therapy in Sport, 23, 93-98.
14. Nohren, B., Davis, I., Hamill, J. (2007). Prospective study of the biomechanical factors associated with iliotibial band syndrome. Clinical Biomechanics, 22, 951-956.
15. Sinclair, J., Taylor, P. J., Currigan, G., Hobbs, S. J. (2014). The test-retest reliability of three different hip joint centre location techniques. Movement & Sport Sciences-Science & Motricité, 31-39.
16. Sinclair, J., Hebron, J., Taylor, P. J. (2015). The test-retest reliability of knee joint center location techniques. Journal of Applied Biomechanics, 31(2), 117-121.
17. Graydon, R. W., Fewtrell, D. J., Atkins, S., Sinclair, J. K. (2015). The test-retest reliability of different ankle joint center location techniques. Foot and Ankle Online Journal, 1(11), 1-9.
18. Eslami, M., Begon, M., Farahpour, N., Allard, P. (2007). Forefoot–rearfoot coupling patterns and tibial internal rotation during stance phase of shod versus barefoot running. Clinical Biomechanics, 22, 74–80.

19. Foch E, Reinbolt JA, Zhang S, Milner CE. Association between iliotibial band syndrome status and running biomechanics in women. Proceedings of American Society of Biomechanics. 2013; Omaha, NE.
20. Sinclair, J. K., Taylor, P. J., Liles, N. (2019). Effects of running with minimal and conventional footwear in habitual and non-habitual users; a musculoskeletal simulation and statistical parametric mapping based approach. Footwear Science (In press - https://www.tandfonline.com/doi/full/10.1080/19424280.2019.1683619).
21. Sinclair, J., Stainton, P., Sant, B. (2018). The effects of conventional and oval chainrings on patellofemoral loading during road cycling: an exploration using musculoskeletal simulation. Sport Sciences for Health, 14(1), 61-70.
22. Sinclair, J., Richards, J., Selfe, J., Fau-Goodwin, J., Shore, H. (2016). The influence of minimalist and maximalist footwear on patellofemoral kinetics during running. Journal of Applied Biomechanics, 32(4), 359-364.
23. Sinclair, J., Butters, B., Brooks, D., Stainton, P. (2018). Effects of a prophylactic knee bracing on patellofemoral loading during cycling. Sport Sciences for Health, 14(3), 645-654.
24. Sinclair, J., Brooks, D., Stainton, P. (2019). Sex differences in ACL loading and strain during typical athletic movements: a musculoskeletal simulation analysis. European Journal of Applied Physiology, 119(3), 713-721.
25. Birnbaum, K., Siebert, C. H., Pandorf, T., Schopphoff, E., Prescher, A., & Niethard, F. U. (2004). Anatomical and biomechanical investigations of the Iliotibial tract. Surgical and Radiologic Anatomy, 26(6), 433-446.

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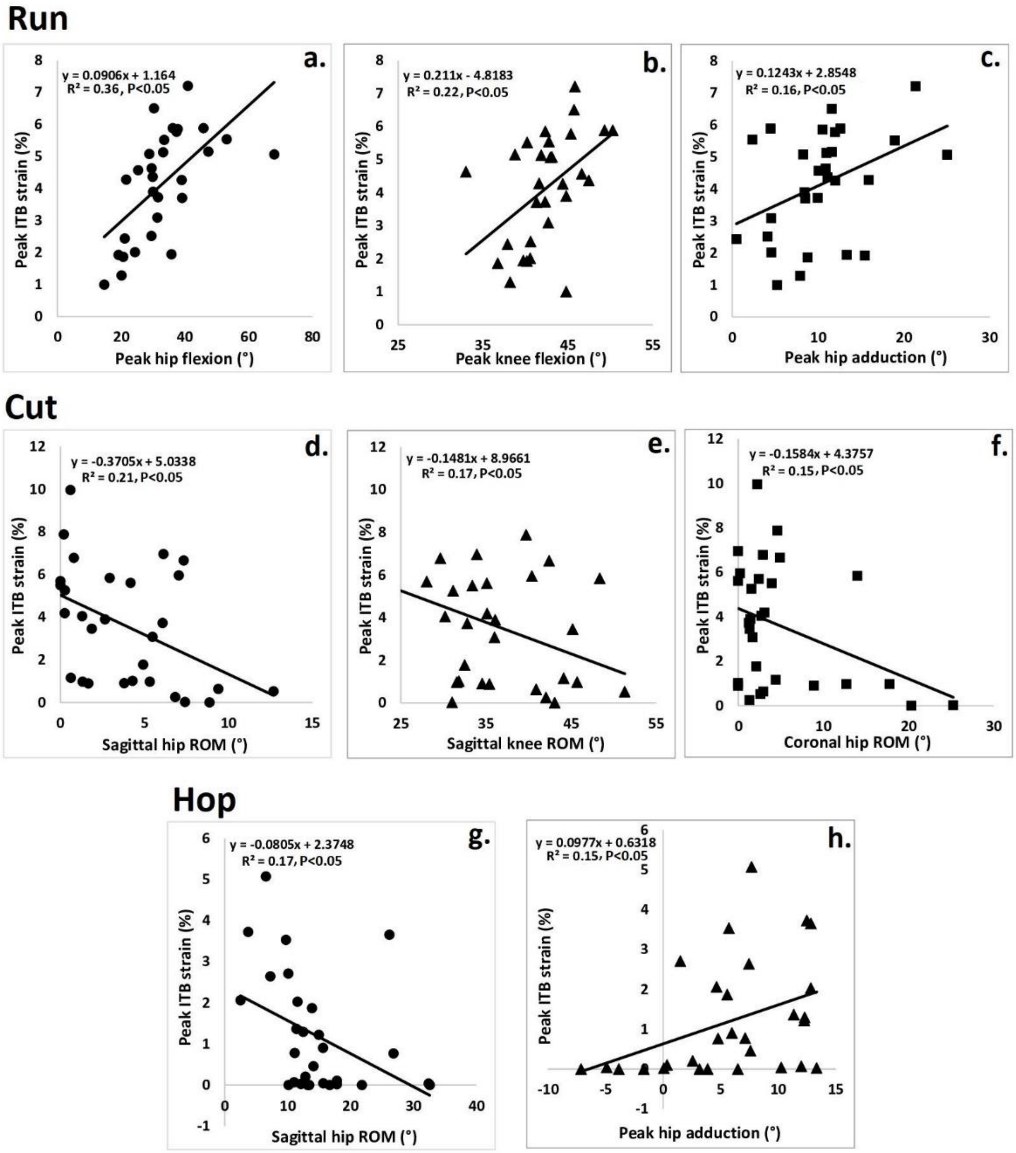

Figure 1: Peak ITB strain as a function of the peak hip flexion (a), of the peak knee flexion (b) and of the peak hip adduction (c) in the run condition; Peak ITB strain as a function of the sagittal hip ROM (d), of the sagittal knee ROM (e) and of the coronal hip ROM (f) in the cut condition; Peak ITB strain as a function of sagittal hip ROM (g) and of the peak hip adduction (panel h) in the hop condition.

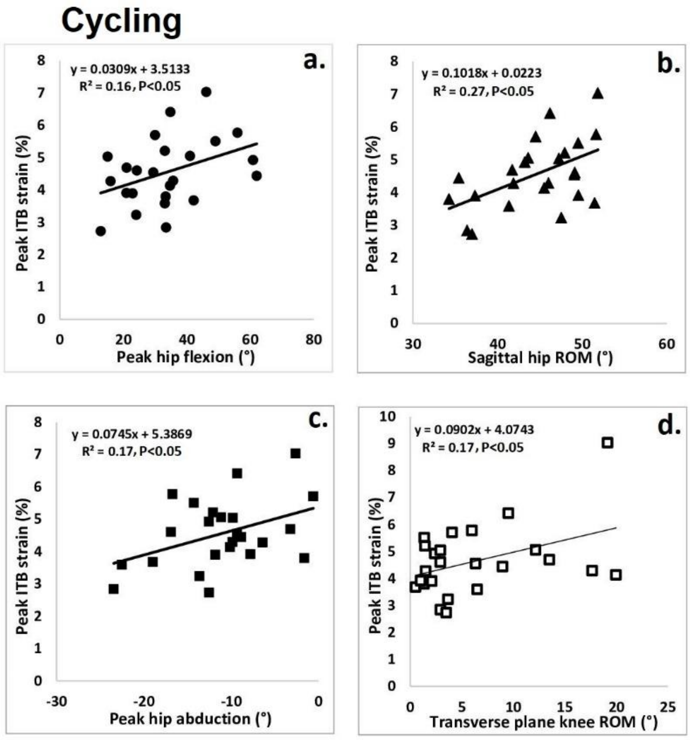

Figure 2: Peak ITB strain as a function of the peak hip flexion (a), of the sagittal hip ROM (b), of the peak hip abduction (c) and of the transverse plane knee ROM (d) in the cycling condition.

Table 1: Iliotibial band and kinematic data (mean, standard deviations and 95% CI's) for experiment 1.

	Males											
	Run				**Cut**				**Hop**			
	Mean	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**
Duration of impingement (ms)	26.0 #***, ‡***	5.6	22.8	29.2	22.9	9.6	17.3	28.4	20.9	9.5	15.4	26.4
Relative duration of impingement (%)	11.0 #***	2.4	9.6	12.4	8.3	3.6	6.2	10.4	10.7 #***	5.6	7.5	14.0
Peak iliotibial band strain (%)	3.9 ‡***	1.9	2.8	4.9	3.1 ‡***	2.7	1.6	4.6	0.9	1.1	0.2	1.5
Peak iliotibial strain velocity (%/s)	42.7 ‡***	15.8	34.0	51.4	51.0 ‡***	33.6	32.4	69.6	25.5	17.5	15.8	35.2
	Females											
	Run				**Cut**				**Hop**			
	Mean	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**
Duration of impingement (ms)	28.5 #***, ‡***	7.8	24.2	32.9	20.4	6.4	16.9	24.0	21.2	7.2	17.2	25.2
Relative duration of impingement (%)	12.1 #***	3.1	10.4	13.8	7.7	2.4	6.4	9.0	11.0 #***	4.0	8.8	13.3
Peak iliotibial band strain (%)	4.4 ‡***	1.5	3.5	5.2	4.1 ‡***	2.8	2.5	5.6	1.5	1.6	0.6	2.4
Peak iliotibial strain velocity (%/s)	47.9 ‡***	11.4	41.6	54.2	46.4 ‡***	32.2	28.6	64.2	27.3	19.0	16.8	37.8

Notes:

= significantly greater than cut (* P<0.05, ** P<0.01, *** P<0.001)

‡ = significantly greater than hop (* P<0.05, ** P<0.01, *** P<0.001)

Table 2: Iliotibial band and kinematic data (mean, standard deviations and 95% CI's) for experiment 2.

	Males																			
	Lateral				**Medial**				**No orthotic**				**Semi-custom**				**Off the shelf**			
	Mean	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**9 C up**
Peak iliotibial band strain (%)	6.6	3.2	4.6	8.5	6.4	3.2	4.5	8.3	6.0	2.7	4.4	7.7	6.7	2.6	5.1	8.2	6.0	2.9	4.3	7
Peak iliotibial strain velocity (%/s)	60.7	29.9	42.6	78.8	56.5	25.3	41.3	71.8	56.0	19.8	44.0	67.9	58.7	22.6	45.0	72.3	54.0	21.4	41.1	66
	Females																			
	Lateral				**Medial**				**No orthotic**				**Semi-custom**				**Off the shelf**			
	Mean	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**9 C up**
Peak iliotibial band strain (%)	9.1	2.9	7.8	10.5	8.8	3.0	7.4	10.2	9.0	3.2	7.5	10.4	8.7	3.1	7.2	10.1	9.0	3.2	7.4	10
Peak iliotibial strain velocity (%/s)	$80.22^{\#***, \ddagger**}$	33.2	64.7	95.7	72.6	29.4	58.8	86.3	$83.01^{\#*, \ddagger*}$	33.6	67.3	98.7	76.7	29.4	62.9	90.5	74.5	31.5	59.8	89

Notes:

= significantly greater than medial (* P<0.05, ** P<0.01, *** P<0.001)

‡ = significantly greater than off the shelf (* P<0.05, ** P<0.01, *** P<0.001)

Table 3: Iliotibial band and kinematic data (mean, standard deviations and 95% CI's) for experiment 3.

	Males																							
	70RPM no-brace				**80 RPM no-brace**				**90 RPM no-brace**				**70RPM brace**				**80 RPM brace**				**90 RPM brace**			
	Mean	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**
Peak iliotibial strain velocity (%/s)	42.5	8.1	37.4	47.6	47.7 ‡***	10.0	41.4	54.1	53.3 #***, ‡***	10.4	46.7	59.9	41.4	7.8	36.5	46.4	48.0 ‡***	7.1	43.5	52.6	52.6 #***, ‡***	10.0	46.3	58.9
	Females																							
	70RPM no-brace				**80 RPM no-brace**				**90 RPM no-brace**				**70RPM brace**				**80 RPM brace**				**90 RPM brace**			
	Mean	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**	**Mean**	**SD**	**95% CI lower**	**95% CI upper**
Peak iliotibial strain velocity (%/s)	46.0	7.7	41.1	50.8	52.5 ‡***	7.8	47.5	57.4	57.7 #***, ‡***	11.1	50.7	64.7	47.3	8.1	42.2	52.4	53.2 ‡***	10.8	46.3	60.0	58.2 #***, ‡***	12.3	50.4	66.0

Notes:
= significantly greater than 70RPM (* P<0.05, ** P<0.01, *** P<0.001)
‡ = significantly greater than 80RPM(* P<0.05, ** P<0.01, *** P<0.001)