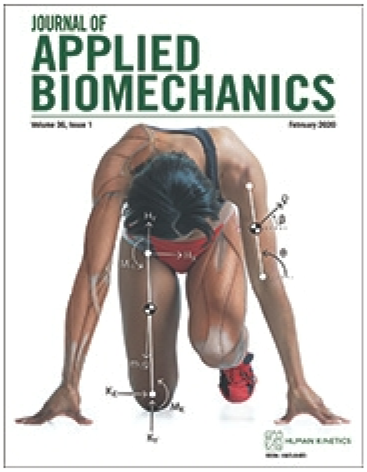

Comparison of transverse plane tibial and frontal plane rearfoot motion and movement coordination between runners with medial tibial stress syndrome and healthy controls

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Comparison of transverse plane tibial and frontal plane rearfoot motion and movement coordination between runners with medial tibial stress syndrome and healthy controls

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Conflict of Interest Disclosure: None.

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Response to Editor and Reviewer Comments

We would once again like to thank the editor and the reviewers for their constructive feedback on the revised manuscript. Please find out point by point responses to each comment below. Alterations within the manuscript are identified by underlined text.

Editor Comments

Comment	Response
Please add a brief description of MTSS (i.e. symptoms), perhaps as a sentence starting on line 42, for readers not immediately familiar with it.	We have added the following information after the opening sentence in the introduction to provide the suggested information to readers. "MTSS is associated with pain along the posteromedial border of the distal aspect of the tibia which occurs primarily during running or exercise[2]." Lines 2 - 4
Figure 1 appears to be highly similar to a figure already published. If it is modified, but similar, please indicate this in the legend, citing the source figure. If it is the same figure, permission to reproduce this figure will be required. Weir, G., van Emmerik, R., Jewell, C., & Hamill, J. (2019). Coordination and variability during anticipated and unanticipated sidestepping. Gait & posture, 67, 1-8.	We believe that the figure is unique enough to not require permission to reprint. We appreciate the figure is similar to that in the Weir article, who's in turn is similar to the one first presented in Needham et al., 2015. We have however revised the figure legend to better highlight the original source of the information in the same manner as Weir. We created the figure ourselves for this publication and have superimposed our own skeletal images on top to highlight

	the motion patterns associated with each aspect of the plot.
The font sizes in Figures 2 and 3 are quite small. Can the authors please increase their size to improve readability?	We have further increased the font size in the figures now, these are now set to a minimal of size 12 font. Hopefully the text will be more reader friendly now.

Reviewer 1

Comment	Response
Thank you for the work updating the analysis and manuscript. The revisions are well done.	We would like to take this opportunity to once again thank the reviewer for their constructive and insightful feedback on the original manuscript.

Reviewer 2

Comment	Response
. I have a couple of minor comments prior to publication. There are a few instances where you write “tibial” instead of “tibia” – eg. Lines 208 and 214.	We have checked the manuscript and revised the terminology where appropriate. This is highlighted by underlined text within the manuscript, in lines 212, 219 and 253.
Lines 113-114: You need to indicate to the reader why you chose 40Hz. So state here that it was a hard setting in the software.	We have now added the following to the end of the identified sentence; “using the built-in hard setting within the Run3D system” (Lines 116 – 117)
Please state how many trials you averaged in your analysis (i.e. 10 stance phases, 20 stance phases). Also make it very clear that you didn’t calculate the coupling angle for each trial and then average with circ stats – and that you just measured the coupling angle on the average CA for each subject and then averaged that with circular stats. This may have significantly impacted your results. This should also be stated in your limitations section where you mention CV.	Data were averaged over 40 – 50 stance phases within the Run3D system, with the variance linked to the system using a time based metric to determine the duration of the recording and differences in step frequency between participants. This information has now been added within the method in line 120. We have made a minor modification to the sentence describing how the coupling angles were calculated to further highlight that individual mean motion patterns were used within the calculation. The sentence on lines 150 - 151 now reads; “The coupling angle was calculated using equation 1 on an individual basis using each participants’ mean tibial rotation and rearfoot motion patterns output by the Run3D system, with group

	mean coupling angles calculated using circular statistics." We have also highlighted that mean data were extracted from the Run3D system earlier within the method now to reiterate this point (line 124). We have added additional information into the CV sentence within the limitations section of the discussion to identify the use of mean data to calculate the coupling angle on a participant level as limitation of the work. The sentence now reads; "Not being able to access the individual trial data resulted in the need to utilise participants mean motion patterns to calculate the coupling angle and also that movement coordination variability, which has also been linked to injury risk[22], could not be calculated as this requires the users to calculate the coupling angle during each of the trials recorded" (lines 240 - 241)
Lines 140-141: You calculated the T2 statistic in this instance, so modify this sentence to reflect that.	Thank you for identifying this terminological error. We have corrected the sentence in line with your comment (line 143).
Lines 152-155: This approach has already been advanced in the Needham 2015 paper which is reference #14. Instead reference that paper.	The highlighted aspect of the sentence has been revised to cite the Needham paper an reads;

	"Utilising the terminology proposed by Needham et al[14]" (Line 155)
Figure 3: The * on the graph is missing to indicate the significant difference between in-phase tibia.	Thank you for the diligent review and picking up on this. We have now added the * to figure 3.
Discussion Lines 217-220: I apologize I didn't pick up on this in the last review – I wonder whether this statement is a little bold as there is an abundance of evidence stating the opposite. Soften these conclusions and incorporate other evidence to present both perspectives.	We appreciate that the statement does go against the typically approaches utilised which largely, in our opinion, are developed off the back of traditional running injury paradigms and that the wording of the identified section may be excessively bold. As such we have softened this section and clearly highlighted that this suggestion contrasting what would typically be promoted. "In contrast to conventional approaches which would look to reduce rearfoot eversion in line with tradition running injury paradigms, these findings suggest interventions which look to increase the duration of rearfoot eversion may actually be beneficial for the MTSS group by improving the in-phase coordination of the rearfoot and tibia, in turn reducing the torsional stress placed upon the tibia which may decrease the likelihood of developing MTSS. This suggestion, while based on the evidence gathered within this study, is however speculative and requires further exploration." Lines 220 – 221 & 225 - 226

May 13, 2020

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Comparison of transverse plane tibial and frontal plane rearfoot motion and movement coordination between runners with medial tibial stress syndrome and healthy controls

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Conflict of Interest Disclosure: None.

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Abstract

Medial tibial stress syndrome (MTSS) is a common running related injury. Alterations in movement patterns and movement coordination patterns have been linked to the development of overuse injuries. The aim of this study was to compare transverse plane tibial and frontal plane rearfoot motion and the coordination of these movements between runners with MTSS and healthy controls. Ten recreational runners with MTSS and ten healthy controls ran at 11km.hr^{-1} on a treadmill. A three-camera motion analysis system, operating at 200Hz, was used to calculate tibia and rearfoot motion. Stance phase motion patterns were compared between groups using multivariate analysis; specifically, Hotelling's T^2 test with statistical parametric mapping (SPM1D). A modified vector coding technique was used to classify the coordination of transverse plane tibial and frontal plane rearfoot motion. The frequency of each coordination pattern displayed by each group was compared using independent samples t tests. Individuals with MTSS displayed significantly (p = .037, d = 1.00) more anti-phase coordination (tibial internal rotation with rearfoot inversion) despite no significant (p > .05) differences in stance phase kinematics. The increased anti-phase movement may increase the torsional stress placed upon the medial aspect of the tibia contributing to the development of MTSS.

Keywords: running; injury; vector coding; statistical parametric mapping; kinematics

Word Count: 2,831 words

Introduction

Medial tibial stress syndrome (MTSS) is one of the most common lower limb injuries associated with recreational running, with incidence rates between 13.6% and 20% [1]. MTSS is associated with pain along the posteromedial border of the distal aspect of the tibia which occurs primarily during running or exercise[2]. Whilst the aetiology of MTSS remains difficult to determine[2,3], there have been considerable efforts to identify the risk factors associated with developing this injury. Systematic reviews[3-5] have been published which identify increased body mass index, plantarflexion range of motion, hip internal/external rotation range of motion, reduced lean calf girth and a pronated foot type as intrinsic risk factors associated with the development of MTSS[3-5]. The majority of existing studies have explored the relationship between static measures and MTSS, the relationship between dynamic foot motion and MTSS has received less attention within the literature.

Traditional running injury paradigms link excessive rearfoot pronation with the development of running related injuries[7,8], on the premise that increasing the magnitude or duration of pronation would lead to abnormal loading or stresses being applied to the lower limb, in particular the tibia[9]. Increased rearfoot eversion or eversion velocity, measures typically used to quantify the magnitude and rate of foot pronation, have been reported in participants who had or later developed lower limb injuries compared to healthy controls during running[8-10]. Comparable findings have been reported within studies which compared RF eversion between healthy controls and MTSS groups during walking[11] and running[6]. While this information provides some evidence linking rearfoot eversion and MTSS specifically, these studies have compared discrete variables extracted from stance phase kinematics between healthy and MTSS or injured populations. More advanced statistical methods, such as statistical parametric mapping (SPM), enable the comparison of kinematic waveforms, in turn providing a more in-depth comparison of movement patterns between populations and removing the need to subjectively preselect variables of interest[12].

Furthermore, no studies, to the authors knowledge, have explored tibial rotations between healthy and MTSS groups. Rearfoot eversion has been shown to be associated with tibial internal rotation due to the coupling of the calcaneus and the tibia, via the talus[7]. As such increased rearfoot eversion may be accompanied by increased internal rotation of the tibia. Concurrent exploration of both rearfoot and tibial kinematics would enable the coupling between these motions to be compared between MTSS and healthy cohorts. Exploration of joint coupling has previously been proposed and utilised as a means of evaluating injury aetiology[13] and may help to elucidate potential mechanisms for the development of MTSS. Relatively recent advancements in vector coding techniques[14-16] enable the coordination of joint couples to be explored from angle-angle plots, with coordination patterns being described as either in-phase (two segments rotating in the same direction) or anti-phase (two-segments rotating in opposite directions), with proximal or distal segment dominance (Figure 1).

Therefore, the aim of this paper was to compare transverse plane tibial and frontal plane rearfoot motion and the coordination of these movements between runners with MTSS and healthy controls. Three hypotheses were tested within this study; tibial internal rotation and rearfoot eversion would be greater in the MTSS group, and the coordination of transverse plane tibial and frontal plane rearfoot motions would differ between MTSS and healthy groups.

Methods

A total of 20 male recreational runners participated in this study, comprised of 10 runners (age: 32 ± 8 y; height: 1.80 ± 0.05 m; mass; 78 ± 8 kg) with MTSS and 10 pain free controls (age: 34 ± 9 y; height: 1.76 ± 0.10 m; mass; 75 ± 10 kg). Inclusion in the study required all participants to be; male, aged between 18-45 years, running a minimum of 15k per week, comfortable running on a treadmill, pain when running 2/10 or below on a visual analogue scale, not wearing orthoses, no history of gait retraining, or other musculoskeletal injury other than MTSS at the time of testing. Inclusion in the MTSS group were in line with the inclusion criteria and pre-existing criteria described by Winters et al[17] for MTSS. Specifically, the MTSS group displayed pain along the lower medial boarder of the tibia for more than 5cm upon palpation which was assessed prior to commencement of testing sessions for this group by a trained podiatrist (NK) at the commencement of testing for those within this group. Prior to data collection participants provided written informed consent form and ethical approval for the study was granted by the University of Brighton School of Health Sciences Research Committee.

Participants attended a single testing session lasting approximately 45 minutes in which they were asked to run in their own running shoes, at a standardised speed of 11km.hr^{-1}, to remove any potential speed related changes in kinematic profiles, for 5 minutes on a Sole F65 treadmill (Sole Fitness, Salt Lake City, Utah, USA). Kinematic data were collected continuously for the first 30 seconds of the final minute of the run. Data collection was undertaken at this time point to provide participants with a familiarisation period to the treadmill in order to reduce discrepancies between treadmill and overground kinematics[18].

Kinematic data were collected using a Run3D automated motion capture system (Run3D Oxford, UK) which consists of three VICON Bonita cameras (Oxford, United Kingdom), sampling at 200Hz. The Run3D system was created to enable 3D motion capture within clinical settings, as such data processing and kinematic modelling are largely automated. Initially, the Run3D system reconstructed and labelled marker trajectories over the entire recording, in this case 30 seconds. Gaps within the marker trajectories were filled using cubic Bezier patches and any trials with excessive marker loss, 50% or above, were deemed invalid and data was recaptured. Prior to data collection the position of the VICON cameras were optimised to minimise marker loss and tracking markers attached to the tibia and rearfoot were visible throughout the stance phase during pilot assessments. Once marker trajectories were labelled and gap filled, they were low pass filtered at 40Hz using the built-in hard setting within the Run3D system. Trials were then partitioned into gait cycles based on the vertical position and orientation of the rearfoot segment, with gait cycles exceeding ± 10% of the median gait cycle length removed. Euler angles were calculated utilising an XYZ cardan sequence of rotations, before mean joint rotations across all remaining gait cycles (40 – 50 gait cycles per-participant) were calculated. Any gait cycles in which the root mean square value was greater than three standard deviations from the mean were removed at this point by the software, before the mean and standard deviation values were updated and output. Within this study we extracted mean frontal plane rearfoot and transverse plane tibial kinematics for each participant analysis, removing swing phase data and time normalising the remaining output to 101 data points corresponding to 100% stance phase duration. All data presented is for the right limb as this was the limb classified as displaying symptoms of MTSS for this group.

The Run3D system tracked the position of nine-millimetre retro-reflective markers attached bilaterally to the lower limbs, in line with the model described by Ferber et al[19]. Of specific interest to this study, the tibia was defined proximally using markers located on the medial and lateral femoral epicondyles, and distally by markers located on the medial and lateral malleoli. The tibia was tracked using cluster of four non-colinear markers attached to a rigid plastic shell and attached to the posterior-lateral aspect of the segment. The rearfoot was defined by two markers placed on vertically on the central aspect of the shoes heel counter, and a third marker located on the lateral aspect of the rear aspect of the shoe. Prior to data collection the Run 3D system was calibrated in line with the manufactures guidelines, only calibrations resulting in residuals of < 0.1 were accepted. A static trial was recorded with participants standing in a relaxed bipedal stance, with the longitudinal axis of each foot 26cm apart and the feet in a neutral alignment; this orientation was standardised using a calibration mat.

Multivariate statistical analysis was undertaken using two-sample Hotelling's T^2 test with SPM to compare transverse plane tibial and frontal plane rearfoot motion between the MTSS and control groups. SPM calculates a statistical parametric map by plotting the T^2-statistic for each time point within the data set and applies random field theory to determine if the average gradient of the t-statistic and clusters of points are above the critical threshold, in turn identifying p values below 0.05[12]. SPM analysis was undertaken in Python using publicly available scripts developed by Pataky[20].

The modified vector coding technique described by Needham et al[14,15] was used to quantify the coordination between transverse plane tibial and frontal plane rearfoot motion. The coupling angle was calculated using equation 1 on an individual basis using each participants' mean tibial rotation and rearfoot motion patterns output by the Run3D system, with group mean coupling angles calculated using circular statistics.

Eq. 1 $$Coupling\ angle = atan\left(\frac{\theta_{rearfoot(i+1)} - \theta_{rearfooti}}{\theta_{tibia(i+1)} - \theta_{tibiai}}\right)$$

Coupling angles were corrected to provide values between 0° and 360° according to Needham et al[15]. Utilising the terminology proposed by Needham et al[14], coordination patterns were classified into one of eight categories based on whether the movements of the tibia and rearfoot were in-phase or anti-phase, with proximal or distal dominance and the direction of the rotations (Figure 1). The percentage of stance spent in each of these categories was calculated and compared statistically using independent samples t tests using SPSS Version 23 (IBM, Chicago, Il). No correction for multiple comparisons were made to the alpha level, which was set at $p < 0.05$. Cohen's d was also calculated to provide an estimate of effect sizes and interpreted as follows; small (0.2), moderate (0.5) and large (0.8) effect[21].

Results

No significant ($p > .050$) differences in transverse plane tibial or frontal plane rearfoot motion were reported between the control and MTSS groups during the stance phase of running gait (Figure 2). A significant difference ($p = .037$, d = 1.00) in transverse plane tibial and frontal plane rearfoot coordination pattern was reported, with the frequency of anti-phase coordination with tibial dominancy (tibial internal rotation with rearfoot inversion) was greater in the MTSS group (10 ± 4%) compared to the control group (6 ± 4%) (Figure 3). No other significant ($p >$ .050, d = 0.0 – 0.4) differences in the frequency of the remaining coordination pattern classifications were reported between the control and MTSS groups.

Discussion

The aim of this study was to compare transverse plane tibial and frontal plane rearfoot motion and the coordination of these movements between runners with MTSS and healthy controls. The findings reject the first two hypotheses proposed with no statistically significant differences in stance phase transverse plane tibia or frontal plane rearfoot motion between the MTSS and control groups. In contrast, the final hypothesis was supported with those in the MTSS group displaying significantly more anti-phase movement, with tibial dominancy, compared to the control group. The findings of this study therefore demonstrate that the coordination, or coupling, pattern of the tibia and rearfoot differ between those with MTSS and healthy controls; even in the absence of any significant changes in tibial or rearfoot motion patterns.

The rearfoot eversion motion patterns displayed by the MTSS and healthy control groups within this study (Figure 2B) were comparable and these contradict the findings of previous studies[6,8,9], which reported significantly increased rearfoot eversion in injured populations compared to healthy controls during running. The disparity between our findings and the previous literature[6,8,9] is likely due to the inclusion criteria for the injured group. While the present study compared those with MTSS alone to a healthy control group, all the previous studies[6,8,9] have utilised injured populations which do not exclusively contain individuals with MTSS. Pooling of multiple injuries into a single injured population is likely to introduce a cross over effect with risk factors associated with one condition masking those associated with another. As such it seems pertinent, especially due to the discrepancies in the findings identified, that comparisons are made between populations with a specific injury and healthy controls as this may help to better understand the aetiological risk factors associated with that injury, which may in turn help to develop more specific and successful (p)rehabilitation interventions.

Despite a lack of significant changes in tibial internal rotation or rearfoot eversion between groups, the MTSS did display significantly altered coordination patterns. This finding suggests that it is the coordination of the movement between the tibia and rearfoot, as opposed to the discrete motion of either of these segments, which is potentially more important to understand the development of MTSS. Increased anti-phase movement in the MTSS group, which appears to be due to increases in the anti-phase movement around 30-40% of the stance phase (based on visual assessment of Figure 3), may increase torsional stresses placed upon the tibia at this time point, as the rearfoot begins to invert while the tibia continues to internally rotate. Interestingly, this finding conflicts with traditional injury paradigms which link excessive eversion and tibial internal rotation to the development of running injuries. Excessive eversion has been assumed to result in increased tibial internal rotation which would result in an in-phase movement coordination pattern rather than the anti-phase pattern displayed by the MTSS group within this study. However, logically increasing the torsional stress placed upon the tibia would likely lead to higher forces acting upon the medial aspect of the bone and in turn increasing the risk of MTSS. Further work is required to explore whether the increased anti-phase movement does relate to significant increases in torsional stresses.

While traditional approaches to reducing running injury risk have focused on reducing rearfoot eversion through footwear or orthotic interventions[7], this may potentially increase the anti-phase coordination pattern displayed by the MTSS group. Visual inspection of Figure 2B shows that the MTSS group begin to invert before 40% of the stance phase, yet the tibia continues internally rotating until closer to 50% of the stance phase. The impact of the prolonged tibial internal rotation upon the joint coupling is evident within the angle-angle plot displayed in Figure 2C. In contrast to conventional approaches which would look to reduce rearfoot eversion in line with tradition running injury paradigms, these findings suggest interventions which look to increase the duration of rearfoot eversion may actually be beneficial for the MTSS group by improving the in-phase coordination of the rearfoot and tibia, in turn reducing the torsional stress placed upon the tibia which may decrease the likelihood of developing MTSS. This suggestion, while based on the evidence gathered within this study, is however speculative and requires further exploration

The findings of this work must be interpreted in light of the limitations. Firstly, the MTSS group were recruited on the basis they had this condition at the time of testing and as such there is the possibility that the movement and coordination patterns displayed by this group are a result of, as opposed to the cause of, this injury. However, a movement strategy which increases the anti-phase movements of the tibia and rearfoot seems an unlikely preventative solution once MTSS has been developed, as the opposing movement of the two segments around midstance would likely increase the torsional stresses placed upon the tibia and in turn increase the risk of injury. Larger scale case control and more prospective studies designs would be required to confirm this hypothesis. The use of the Run3D system is another potential limitation of this study. As detailed within the method section, the Run3D system is designed to be used within a clinical setting, to decrease the time constraints placed upon users, and as such the system outputs mean and standard deviation values only for the trials recorded, while also limiting the user's ability to manipulate the data processing pipeline. Not being able to access the individual trial data resulted in the need to utilise participants mean motion patterns to calculate the coupling angle and also that movement coordination variability, which has also been linked to injury risk[22], could not be calculated as this requires the users to calculate the coupling angle during each of the trials recorded. Additionally, footwear was not standardised within this study and variance in the stability features built into different participants running shoes may have influenced kinematic patterns in different ways.

The findings of this study suggest that tibial internal rotation and rearfoot eversion do not differ significantly between individuals with MTSS and healthy controls. However, the MTSS group displayed significantly increased anti-phase coordination with tibial dominancy during the stance phase of the running gait cycle. The significant increase in anti-phase motion displayed by the MTSS groups appears to be related to the rearfoot beginning to invert while the tibia is still internally rotating, which would likely increase the torsional stress placed upon the tibia. Interventions which improve the coupling of rearfoot eversion and tibial internal rotation may help to reduce the risk of developing MTSS, by increasing the in-phase movements of these segments.

Acknowledgements

We would like to thank Run3D for providing additional information relating to the processing of data within their software, which helped to increase the clarity of the manuscript.

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Figure Legends

Figure 1. Coordination pattern classification based on the coupling angle displayed as a polar plot using the terminology described by Needham et al.,[14]. Visual illustrations of the segment motions associated with each quadrant of the polar plot are overlaid. NOTE: At 0° and 180° the proximal segment is rotating with no movement of the distal segment, and at 90° and 270° the distal segment is rotating with no movement of the proximal segment

Figure 2. (A) Transverse plane tibial and (B) frontal plane rearfoot motion, (C) angle-angle diagram during the stance phase of running gait for the control (black line) and medial tibial stress syndrome (MTSS) (grey line) groups. (D) T^2 statistic from SPM analysis and critical threshold (horizontal dashed lines) displayed.

Figure 3. Mean coupling angle during the stance phase of running gait for the control (black) and medial tibial stress syndrome (MTSS) (grey) groups, and the frequency with which each coordination pattern is evident throughout the stance phase. * $p < 0.05$

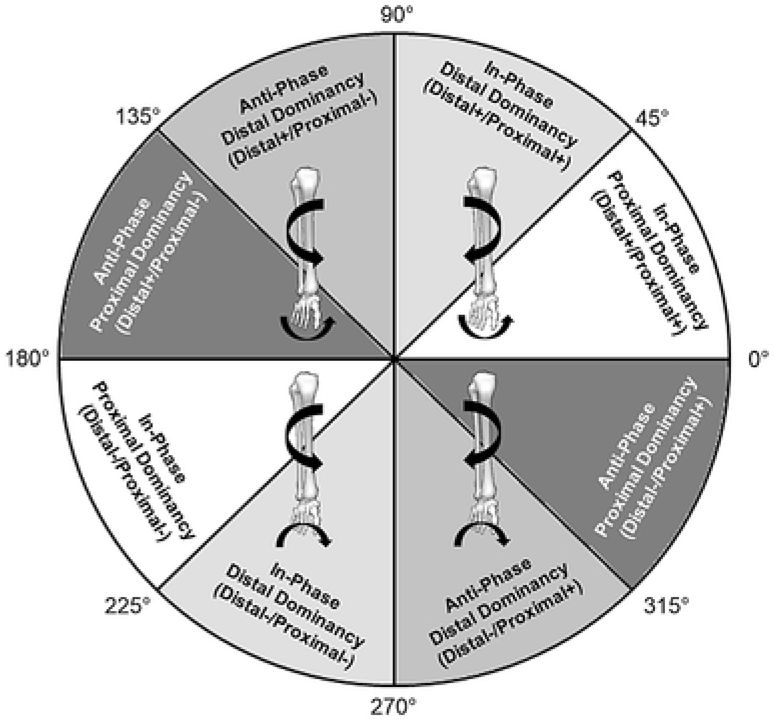

Figure 1. Coordination pattern classification based on the coupling angle displayed as a polar plot using the terminology described by Needham et al.,14. Visual illustrations of the segment motions associated with each quadrant of the polar plot are overlaid. NOTE: At 0° and 180° the proximal segment is rotating with no movement of the distal segment, and at 90° and 270° the distal segment is rotating with no movement of the proximal segment

34x31mm (300 x 300 DPI)

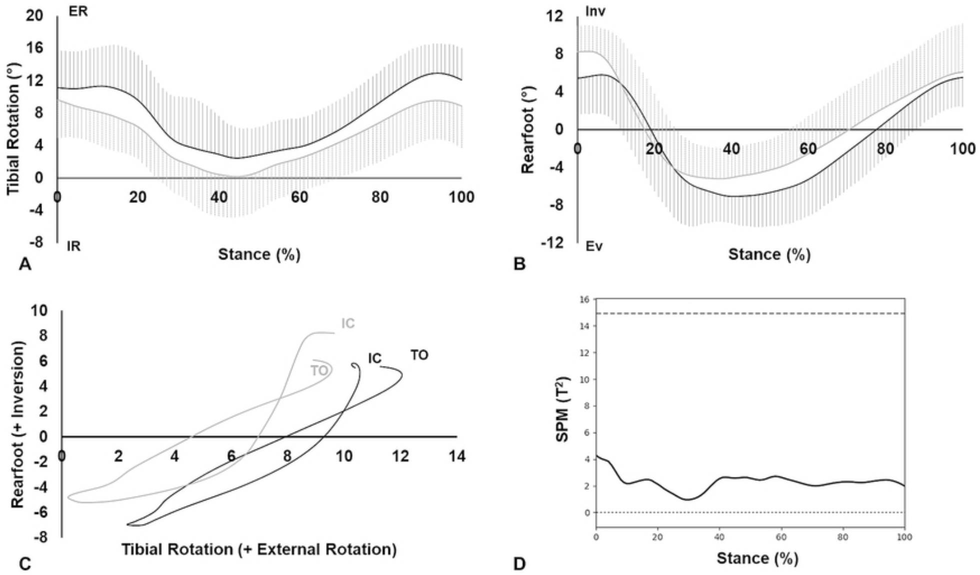

Figure 2. (A) Transverse plane tibial and (B) frontal plane rearfoot motion, (C) angle-angle diagram during the stance phase of running gait for the control (black line) and medial tibial stress syndrome (MTSS) (grey line) groups. (D) T2 statistic from SPM analysis and critical threshold (horizontal dashed lines) displayed.

75x44mm (300 x 300 DPI)

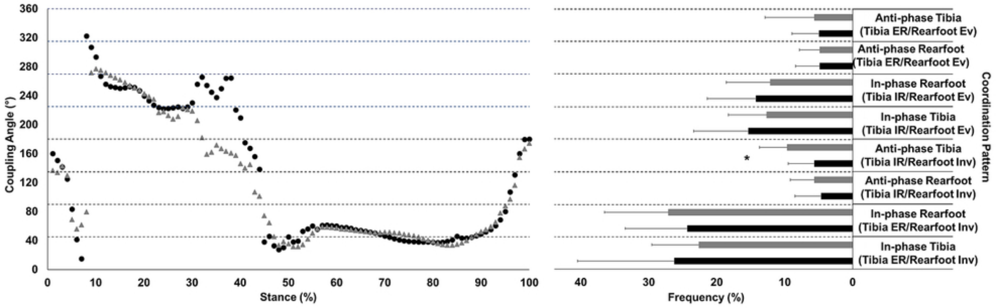

Figure 3. Mean coupling angle during the stance phase of running gait for the control (black) and medial tibial stress syndrome (MTSS) (grey) groups, and the frequency with which each coordination pattern is evident throughout the stance phase. * $p < 0.05$

83x27mm (300 x 300 DPI)