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ORIGINAL ARTICLE

The Association Between Foot Structure and Foot Kinematics during Slow Running

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Background: Clinicians routinely assess foot posture as part of their assessment and management of foot pathologies. Flat or high arched foot postures have been linked to kinematic deviations and increased foot injuries risk. The Foot Posture Index (FPI) is a valid clinical tool used to classify feet into high arched, normal and flat foot groups and predicts foot function during walking well. Walking and running are distinct locomotion styles, and studies have not been done to correlate FPI to foot function during running. This study aims to investigate the association of FPI scores to foot kinematics during running. The results will

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further inform clinicians who perform static assessment of feet of individuals who are runners.

Methods: Sixty-nine participants had their feet assessed using the FPI scoring system. Based on these scores, the feet were categorised as flat foot, normal arched and high arched. Rearfoot eversion and forefoot dorsiflexion (arch flattening) of the foot were analysed during slow running between 1.4 - 2.2 ms⁻¹. Pearson's correlation was used to analyse the FPI scores on an interval scale, with Cohen's d used to report effect size. One-Way Anova and a Bonferroni Post-hoc test was used to analyse data by category. Level of significance was set at p<0.05.

Results: Thirty four flat feet, 26 normal arched feet, and 9 high arched feet were analysed. The FPI scores correlated significantly with rearfoot eversion (moderate effect size) and forefoot dorsiflexion (low effect size). Rearfoot eversion was greatest in the flat foot, followed by the normal arched foot and the high arched foot. Forefoot dorsiflexion was significantly higher in the flat foot compared to the high arched group.

Conclusions: FPI scores are positively correlated with rearfoot eversion and forefoot dorsiflexion during running. Clinicians can use this information to aid their foot assessment and management of individuals who are runners.

The foot can be classified into three foot postures – the high arched foot posture, the normal foot posture and the flat foot posture. The high arched foot is also sometimes referred to as the supinated foot and is defined as a foot with a higher arch profile than the normal arched foot. The flat foot posture is also sometimes referred to as a pronated foot, and is defined as a foot

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with a lowered arch profile compared to the normal arched foot. Foot posture is an important aspect of clinical assessment. High and flat arched foot postures have been found to exhibit different gait patterns^{1,2}, and an increased risk of injury occurrence^{3,4,5}.

Static measures of foot posture have been used in clinical settings which include direct measurements of the foot such as measuring navicular drift and drop⁶ and calcaneal eversion angle⁷. There are also indirect measurements such as measuring various indices e.g. Footprint Index⁸ and the Arch Index⁹ from footprints. However, these foot classification methods have not been able to consistently predict foot movements during dynamic gait, i.e. a foot classified as a flat foot using static measurement did not always produce the expected gait deviations of a flat foot². Furthermore, these methods only allowed the classification of the foot into normal arched and flat foot postures. Since there are three foot posture classifications, studies that did not include high arched foot postures could be considered incomplete. Foot classification methods that included the classification of a high arched foot will allow a comprehensive study of the effect of foot posture on gait patterns.

The Foot Posture Index (FPI) is a validated tool¹⁰ that is commonly used by clinicians to classify feet into pronated and supinated foot postures. The FPI has been found to correlate well with other measures of foot postures^{11,12}. It was also found to be a reliable measurement tool for arch height in adults¹³ and highly associated with rearfoot eversion¹⁴ and navicular height and drop¹⁵ during walking gait. However, walking and running are distinctly different locomotion styles and the association between foot posture, as measured by the FPI, and

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running gait has not been evaluated. This study aims to investigate the association between the FPI scores and foot movements during running.

The FPI relies on six validated criteria to classify feet into supinated, normal and pronated categories, with supinated feet equating to high arched feet, and pronated feet equating to flat feet. The FPI considers aspects of the foot in three planes, and in multiple segments¹⁶. Chuter¹⁰ studied the walking gait of 40 individuals whose feet were classified using the FPI. The FPI was found to correlate positively to frontal plane rearfoot maximum eversion ($r=0.92$, $p<0.05$) meaning, the higher the FPI score (flatter feet), the greater the magnitude of rearfoot eversion. Linear regression analysis showed that 85% of variance in maximum rearfoot eversion can be explained by FPI scores ($p<0.00$), indicating that FPI scores are highly predictive of rearfoot eversion angles. Unfortunately, only rearfoot eversion was analysed and reported. In examining foot function, the movement of the arch would be an important aspect to investigate. Nielson et al.¹¹ found that the drop in arch height during gait, as measured by a navicular drop and minimal navicular height from the ground correlated positively with FPI scores, with FPI explaining 13.2% of the variance in navicular drop and 45.0% in minimum navicular height. These two studies suggest that foot posture affects rearfoot and forefoot movements during walking.

Walking and running are distinctly different locomotion styles. During walking, there is a double support phase where both feet are supporting the body (i.e. one foot is at the toe-off phase while the other foot is at the heel strike phase), followed by a single support phase where one foot is on the ground. During running, there is a 'float phase' where both feet are

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not on the ground, followed by a single limb support phase. This results in a difference in timing of events and muscular activation in the trunk and lower limb¹⁸. Kinematically, compared to walking, there is considerably more flexion in the foot joints during running where the limb acts in a more 'spring-like' fashion¹⁷. The kinematic coupling within the foot joints have also been found to be greater when running than walking¹⁸, namely there was more rearfoot eversion and forefoot dorsiflexion (arch deformation) in running than walking. Kinetically, the load taken by the feet increases from 1.2 times of bodyweight when walking to 2.5 times of bodyweight when running; the loading rate also increases from 8 times of bodyweight per second when walking to 30 times of bodyweight per second¹⁹. A previous study investigated the association between the longitudinal arch angle and arch deformation during walking and running and found that arch profile explained 85.4% of the variance in longitudinal arch deformation during walking and 84.6% of the variance in longitudinal arch deformation during running²⁰. This implies that foot posture affect arch movements during running as well.

Within running, foot strike pattern and kinematics changes with speed; foot strike patterns have been observed to change from rearfoot to midfoot strike when running speed was increased from 3.0 ms⁻¹ to 6.0 ms⁻¹ and kinematic changes are a result of speed rather than foot posture²¹. In looking for an appropriate running speed to study, Segers et al.²² found that the normal walk-to-run transition speed was approximately 2.0 ms⁻¹, denoted by the presence of a 'flight phase' when both feet are off the ground. This was agreed by Farris and Sawicki²³ who found that at 2.0 ms⁻¹, it was more efficient to run than walk from an energy consumption perspective and suggested that this was why most subjects would prefer to break into running

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from walking at this speed. Therefore, in this study, a slow run (running at around 2.0 ms^{-1}) was selected as the movement mode to examine for changes in gait that may be attributed to foot posture and not to other confounding factors such as running speed.

Since walking and running are distinct locomotive styles, an investigation into the relation between FPI scores and foot movement during running is warranted. The correlation of FPI scores to foot kinematics during running has not yet been fully investigated. This study will assess participants with flat, normal and high arched feet, and consider foot movements during slow running. The movement of the rearfoot in eversion (in the frontal plane) and the forefoot in dorsiflexion (arch deformation in the sagittal plane) during running has been selected for examination. The results of this study will provide clinicians with a better understanding on how these scores relate to foot function during running, and will aid them in assessing individuals who are runners.

Methods and Materials

Participants and screening measures:

Participants were recruited from a convenient sample of the general public and students in the Nanyang Technological University (Singapore). The inclusion criteria were: participants had to be between 21- 45 years of age, be self-reported recreational heel/ rearfoot strike runners, and be able to run at least 10 minutes barefoot on a treadmill. Exclusion criteria also consisted of participants who had foot deformities, surgeries and/or foot pain six months prior to data collection, have BMI greater than 36 kgm^{-2} , suffer from medical conditions that alter gait

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pattern, such as stroke and Parkinson's disease, and have known allergies to adhesives and double sided tape.

All procedures were approved by the Institutional Review Board (IRB-2012-09-004) of the Nanyang Technological University (Singapore). All trials were conducted in the Sports Biomechanics Laboratory situated in the Block 5, Level B3, Room 01, Physical Education and Sports Science, Nanyang Technological University. All participants received an information sheet providing details and requirement of participation. All participants provided written informed consent prior to the commencement of the study.

Foot posture classification

A podiatrist (MH), with 2 years of clinical experience using the FPI, performed all clinical assessments of foot posture. The participant was asked to stand in an area where the tester would be able to move freely around the subject to assess the foot. The participant marched on the spot for a few steps before settling into a comfortable relaxed stance position, with arms to the side. The FPI was scored based on the observation of six criteria of foot posture. Each criterion was scored using a 5 Point Likert-type scale, from -2 to +2, resulting in a score on a continuous scale between -12 to +12. A score ranging from -12 to -1 classified the foot as high arched, a score ranging from 0 to 5 classified the foot as normal arched and a score ranging from +6 to +12 classified the foot as flat footed.

To ensure reliability of the assessor, these measurements were pre-tested on 8 participants (16 feet), where each foot was scored according to the FPI on two sessions 3

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months apart. The scores for the first session was not available to the assessor during the second session to reduce scoring bias. The FPI raw scores between two sessions showed good correlation; the single measures Intra-rater correlation coefficient (ICC) was 0.92 with 95% confidence interval (CI) = 0.75-0.97. Kappa value for FPI categorisation also showed good agreement, $K=0.87$ ($p<0.01$). This shows that MH was a consistent and reliable assessor.

Kinematic Gait Analysis

Three dimensional kinematic data was collected using a 3D motion capture system (Motion Analysis Corporation, Santa Rosa, USA) with 6 Hawk cameras (capturing at 60Hz) positioned around an instrumented treadmill (Kistler. Gaitway, Kistler Instrument Corporation, Amherst, NY). The side bars of the treadmill were removed to prevent occluding the view of the Hawk cameras. This marker set used for this study was adapted from the Oxford Foot Model²⁴ marker set. Eleven 25mm reflective markers were placed on different parts of the lower limb (Figure 1) to obtain the required segmental movement of the foot. The markers were placed on the lateral fibula head and the medial tibial condyle, medial and lateral malleolus, medial and lateral calcaneus, navicular tuberosity and styloid process of the 5th metatarsal, the medial aspect of the first and the lateral aspect of the fifth metatarso-phalangeal joint and the medial first inter-phalangeal joint. One of the adaptations to the Oxford Foot Model marker set was the absence of a posterior calcaneal marker. This was because during the pilot tests, the posterior calcaneal marker kept getting displaced, likely due to the rapid dorsiflexion and plantarflexion of the foot during heel strike running and vibration due to impact. Therefore, the marker set was modified

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with corresponding adjustments to the foot and leg model created for kinematic joint angle analyses.

The participants ran on an instrumented treadmill between the speeds of 1.4 – 2.2 ms⁻¹. This range of speed was selected based on a pilot study which measured the self selected comfortable running speed of 8 participants. The mean self-selected comfortable running speed was 1.8 ± 0.4 ms⁻¹. Therefore, in the main study, participants who were unable to run comfortably within this range of speeds were excluded from the study at this juncture. The instrumented treadmill provided real-time kinetic data on vertical ground reaction force (vGRF) during the participant's trial. The participant is defined as running when the kinetic vGRF graph shows distinct non-overlapping left and right graphical readings, indicating single support locomotion or a float/ flight phase. The participants continued running at this constant pace for six minutes before collection of the kinematic data commenced. Six minutes of running was the time previously suggested for participants to acclimatise to running on a treadmill^{25,26} All participants ran barefoot with a heel strike running gait. This is confirmed with the presence of a vertical impact peak observed in the real-time vGRF graphs provided by the instrumented treadmill software. Ten seconds of continuous data was collected. If an error occurred, the trial was abandoned and a new trial repeated after a five minute rest period to prevent participant fatigue. These errors include inconsistent heel strike running gait pattern as observed from the absence of an impact peak in the vGRF graph output, and/or accidental marker displacement during the running trial.

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Data Processing

Five consecutive consistent foot contacts were selected from the ten-second running trial for analysis. The data was filtered using a Butterworth low pass, fourth order, zero phase filter at 10 Hz²⁷. The data were then exported in C3D format onto the Visual 3D software (C-motion Inc, Germantown, USA) for further processing.

A four rigid segment leg and foot model was created consisting of the leg, rearfoot, forefoot and first toe to quantify the rearfoot and forefoot dorsiflexion movement (Figure 2). The segments were modelled as simple geometric solids with uniform densities. The modelled leg segment was formed proximally by the marker on the lateral fibular head and the medial tibial condyle and distally by the lateral and medial malleoli markers. The rearfoot segment was formed by the lateral and medial calcaneal markers and distally by the markers on the styloid process of the fifth metatarsal and navicular tuberosity. The forefoot segment was formed proximally by the markers on the styloid process of the 5th metatarsal and the navicular tuberosity and distally by the markers on the fifth and first metatarsophalangeal joint.

Signal processing

The origin of the local coordinate system was located at the proximal endpoint, midway between the medial and lateral location markers. For example, for the leg segment, the local co-ordinate system was located midway between the medial tibial condyle marker and the lateral fibula head marker. When the co-ordinate systems of two segments were perfectly aligned, the angle between them would be zero.

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Joint angles were measured in Visual 3D as previously described by Cole et al (1993)²⁸. To measure the rearfoot eversion angle, a virtual rearfoot was created so that the local coordinate systems of the leg and rearfoot could be aligned. The virtual rearfoot was created where the proximal and distal endpoints were the same as the leg segment, but the markers on the rearfoot (medial and lateral calcaneal and navicular tuberosity and styloid process markers) were used as tracking markers²⁹. The angular movements between the leg and the virtual rearfoot were measured with rearfoot inversion/eversion observed by measuring the movement of the virtual rearfoot segment relative to the leg segment.

As the proximal aspect of the forefoot segment shared the same markers as the distal aspect of the rearfoot, the forefoot segment had only one degree of freedom i.e. the segment was only free to rotate in the sagittal plane. Forefoot dorsiflexion/plantarflexion is observed by the movement of the forefoot segment relative to the rearfoot segment. Both movements are verified manually by visually inspecting the segment movement and the segment coordinate system in Visual3D's Model Builder mode.

The joint angles (signals) were processed within the Visual 3D software and a low pass Butterworth filter at 10 Hz was used to smooth the data and remove noise. The stance phase (from heel strike to toe off) was normalised over 101 frames and the mean values of the variables over five steps were compared between participants.

The determination of heel strike and toe off were adapted from kinematic events according to an algorithm described previously³⁰. Heel strike was determined when the lateral calcaneal marker of the foot began moving backwards on the treadmill. The point in time in

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which the lateral calcaneal marker began moving in the direction of locomotion was labelled as toe off.

The difference between the maximum and minimum values during stance phase was measured as the total range of movement of the joint. The mean and standard deviations of the angular movements throughout five consecutive selected steps were measured. Figure 3 demonstrates a rearfoot eversion graph of a participant. It was noted that there was a slight perturbation in rearfoot movement during the stance phase. This may be due to minor rearfoot movements during running. Manual checking of the data revealed that this was consistent with the other participants and there was no error or artefact. The total range of motion was measured by the subtracting the minimum eversion angle from the maximum eversion angle. Figure 4 shows the forefoot dorsiflexion angle of the same participant. The total range of motion was measured by subtracting the minimum dorsiflexion angle from the maximum dorsiflexion angle.

Statistical Analysis

Descriptive statistics were used to show the incidence of high arched feet, normal arched feet and flat feet, within the sample population. To study the effect of foot posture on rearfoot eversion and forefoot dorsiflexion during slow running, the mean and standard deviation of these two movements between the three foot structures was compared using One –Way ANOVA and a Bonferroni Post-hoc test. A Pearson’s correlation test was also used to find the

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relationship between FPI scores, and rearfoot eversion and forefoot dorsiflexion, and Cohen's d was used to report effect size.

Results

Thirty-eight participants (mean age = 30.5 ± 7 years, mean BMI = $22.7 \pm 4 \text{ kgm}^{-2}$) were recruited for this study.

The distribution of foot structure in this study show that 13% were classified as high arched, 48% were classified as normal arched, and 39% of the feet were classified as flat foot, according to the Foot Posture Index. The mean FPI for the flat foot group was 7.43 ± 1.58 , the normal arch foot was 2.04 ± 1.86 and the high arched foot was -1.50 ± 0.51 .

Figure 5 shows the rearfoot eversion and forefoot dorsiflexion angles amongst the high arched, normal and flat foot groups.

The mean rearfoot eversion was 10.51 degrees (95% CI=8.54 – 12.48), 13.51 degrees, (95% CI = 12.59 – 14.43) and 16.46 degrees (95% CI=15.42 – 17.51) for high arched, normal arched and flat foot groups respectively. A One way Anova analysis showed that the rearfoot eversion differed significantly between foot structures ($F(2,135) = 18.62, p=0.00$). A Bonferroni post-hoc test revealed that differences were significant amongst all three groups. Rearfoot eversion was 21.9% greater in the flat foot compared to the normal foot group (SPSS Bonferroni adjusted $p=0.00$), normal arched foot had 22.2% more rearfoot eversion than the high arched group (SPSS Bonferroni adjusted $p=0.04$) and the flat feet had 56.7% more rearfoot eversion than the high arched group (SPSS Bonferroni adjusted $p=0.00$).

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The mean forefoot dorsiflexion was 10.95 degrees (95% CI=9.67 – 12.23), 16.04 degrees (95% CI = 14.86 – 17.22) and 17.20 degrees (95% CI=15.86 – 18.54) for high arched, normal arched and flat foot groups respectively. Forefoot dorsiflexion was also significantly different between the three groups ($F(2,135) = 4.32, p=0.02$). A Bonferroni post-hoc test showed that the difference was significant between the high arched and flat foot groups only. The Flat foot had 57.1% significantly more forefoot dorsiflexion compared to the high arched foot group (SPSS Bonferroni adjusted $p=0.00$). There was no significant difference between the normal and high arched group (SPSS Bonferroni adjusted $p=0.31$) and normal and flat foot group (SPSS Bonferroni adjusted $p=0.14$).

Pearson's correlation showed that FPI correlated linearly and positively to rearfoot eversion and forefoot dorsiflexion. The correlation coefficient between FPI and rearfoot eversion was $r=0.48$ ($p=0.00$) and forefoot dorsiflexion was $r=0.24$ ($p=0.00$). The Cohen's d value shows a moderate effect size for rearfoot eversion ($d=0.23$) and a low effect size for forefoot dorsiflexion ($d=0.05$).

Discussion

Distribution of foot posture

In this study, foot posture was measured using the Foot Posture Index (FPI) and yielded a score on an interval scale from -12 to +12. This score was used to classify the feet into three distinct groups; high arched, normal and flat foot. This distribution pattern was consistent with the findings of Hillstrom et al.¹ who had a distribution of 20% high arch, 44% normal arch and 36%

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flat feet. The normal arched foot was most common, followed by the flat foot and the high arched foot. The slight differences in percentages could be due to the fact that Hillstrom et al.¹ classified foot posture using different techniques, namely the Valgus Index and Arch Index. Furthermore, as their study was done in a different geographical location, slight differences in foot posture distribution can be expected.

The mean FPI for the flat foot group was 7.43, which was on the lower end of the range of scores for flat foot (+6 to +12). Similarly, the mean FPI for the high arched group was -1.50, which was on the lower end of the range of scores for high arched feet (-12 to -1). The mean FPI score for normal arched feet was 2.04, which was in the middle of the range of scores for normal arched feet (0 to +5). Including high arched subjects with a mean score closer to -6 and flat footed subjects with a mean score of +9 may result in data collected that is more representative of the high arched and flat foot groups. However, it may not be easy finding asymptomatic feet with these FPI scores. For example, a high arched foot with a score of -6 might be quite supinated and may be associated with some pathology such as peripheral neuropathy³¹. People with foot pathologies may be more likely to have severely higher or lower foot type than those who do not have foot pathologies and therefore may be under-represented in the study due to our exclusion criteria. Although, the scores obtained from the sample population may not capture the severely high arched and flat foot conditions, the scores may be more representative of the FPI scores in the general population who have asymptomatic feet.

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Foot posture and foot kinematics

This study showed that for the normal arched foot, the mean rearfoot eversion was 13.5 degrees and the mean forefoot dorsiflexion was 16.04 degrees. These movements were higher compared to the study of Nester et al.³² who found that the mean total range of rearfoot eversion was 8.9 degrees and forefoot dorsiflexion was 3.2 degrees for walking. Our findings show that foot joint movement during running is greater than walking. This is consistent with the findings of Barton et al.³³.

The results showed that flat feet exhibited more rearfoot eversion than normal arched feet and high arched feet. This pattern is consistent with other studies^{10,32}. The results from this study also showed that higher FPI scores were associated with more rearfoot eversion ($r=0.48$). This agrees with the findings of Lee and Jay³⁴ who found that foot posture correlated to rearfoot eversion ($r=0.67$). Although the findings follow the same trend, the correlation in our study was slightly lower possibly because the participants in their study were made to run at a set speed of 2.65 ms^{-1} compared to the participants in this study who ran at a self-selected comfortable pace within a range of $1.8 \pm 0.04 \text{ ms}^{-1}$. Studies have shown that participants who were made to run at a set speed which may not be their self selected pace, may alter their running gait³⁵. As such, the results of our study accounts for the natural changes in rearfoot movements due to running rather than other confounding factors such as the participant being forced to run at a set speed. It is also important to note that one of the criteria for FPI scoring is a measure of the calcaneal inversion/ eversion angle. Although this is a static measure, there is

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a possibility of multicollinearity when FPI is being compared to rearfoot eversion during running.

Looking at forefoot dorsiflexion, which reflects how much the arch flattens, the flat foot showed no significant difference to the normal arched foot. However, a difference was found only when comparing the flat foot to the high arched foot.

In this study, foot posture was scored using the FPI, which allowed classification and comparison of three distinct foot postures, namely the high arched, normal arched and flat foot. When comparing arch movements, it seems the difference could only be elicited when comparing the high arched and flat foot groups. This may infer that the FPI, might be a more sensitive tool to use when assessing runner's feet compared to other static assessment methods that only classify the feet into two groups, such as the navicular drop which only allows the foot to be classified into low arched and normal arched groups.

The result of this study found that FPI scores correlated positively to rearfoot eversion (moderate effect size) and forefoot dorsiflexion (low effect size). Given that the one of the criteria of the FPI was to observe the calcaneal inclination in the frontal plane, it is surprising that although significantly correlation, the effect size was only moderate. The same could be said for forefoot dorsiflexion. One of the criteria for FPI assessed for the congruency of the longitudinal arch profile, implying that FPI should be highly correlated to forefoot dorsiflexion. Yet, the effect size of FPI on forefoot dorsiflexion was low.

This may imply that although significant, other factors need to be considered when performing assessment of the foot and lower limb, in the context of associating these with

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dynamic foot movement. For example, if foot posture did not have a high effect size on rearfoot eversion and forefoot dorsiflexion, then potentially other factors need to be considered that may have a potentially high effect size on these foot movements. These factors may include neurological factors such as proprioception, neuromuscular control of the lower limb and even balance ability. A study was done where the intrinsic foot muscles were electrically stimulated during gait. It was found that by stimulating the abductor-hallucis brevis muscle in the foot, there was less rearfoot eversion and arch deformation during walking gait³⁶. Looking at Figure 3, the rearfoot eversion graph showed minor perturbations during the stance phase. This may implicate muscle activity during heel strike and throughout stance working antagonistically to the extrinsic ground reaction force throughout the stance phase of running gait. This is consistent with the findings of Nester et al.³⁷ that challenges the notion that there is a 'normal' and 'abnormal' gait pattern due to foot posture alone. Human gait is too varied and dependant on multiple factors. Therefore, instead of being focussed solely on foot posture, other factors should be considered as well when assessing the foot.

Limitations

Impact of adapted foot model

The marker set used in this study was adapted from the Oxford Foot Model and a simplified version was used as to create a four segment lower limb model in Visual 3D. This study required the measurement of rearfoot eversion, which is in the frontal plane, and forefoot

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dorsiflexion, which is in the sagittal plane. This current foot model allowed the measurement of these two movements, occurring in two different planes simultaneously.

There were some markers that were used for two segments. For example, the marker on the navicular tuberosity and the 5th styloid process were used to demarcate the proximal aspect of the forefoot segment and the distal aspect of the rearfoot segment. This was deemed enough as only forefoot dorsiflexion angle measurements were required, and not adduction/abduction and inversion/eversion. The practice of having two segments share the same markers is not unique. Simon et al.³⁸ developed the Heidelberg foot model which consists of a 17 marker set model to evaluate the foot divided into rearfoot, forefoot, medial forefoot, lateral forefoot and 1st toe. The measurement of arch height was also done by measuring the angle formed by the line from medial calcaneal marker to the navicular marker, and the line between the navicular marker to the 1st metatarsophalangeal joint marker. This is similar to the protocol used in this study. The mean range of motion reported by Simon et al.³⁸ for the equivalent of rearfoot eversion was 10.0 degrees and forefoot dorsiflexion was 13.2 degrees for 10 participants with no known foot abnormalities. The angles found in our study reported a mean rearfoot eversion of 10.5 degrees and forefoot dorsiflexion of 11.0 degrees for the normal arched group, which is a 0.5 degrees and 2.2 degrees difference respectively. The adapted foot model used in our study produced values close to the Heidelberg foot model, which has been validated to produce repeatable and reproducible measurements required for clinical practice³⁸. Future studies may be done to validate this simplified marker set and foot model used in this study.

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Running conditions

This study investigated foot movements during barefoot running. This is necessary so that markers could be placed on the foot to allow measurement of the angles required for this study. However, in normal circumstances, most runners would run with footwear.

Measurement of foot kinematics when the participant is wearing footwear is controversial as one could argue if the measurements taken were those of foot movement or shoe movement. Studies have been done to measure foot kinematics indirectly. For example, in-shoe pressure measurement systems can be placed inside the shoe, to measure center of pressure trajectories between the foot and shoe interface. Changes in the pressure-time outcomes may infer changes in foot kinematics³⁹. However, direct measurement of foot movements with the use of footwear remains a challenging area in research. Future research investigations may need to devise a way to accurately measure foot movements within a shoe.

The running gait pattern analysed in this study was also specific to a heel strike running gait pattern. Foot kinematics have been reported to differ with different foot strike patterns. In this study, rearfoot eversion differences were found amongst all three foot posture groups. The amount of rearfoot eversion on the three foot types appeared to be associated quite linearly with FPI scores, and consequently the FPI groups (high arched, normal arched and flat foot). But for forefoot dorsiflexion, a difference was only noted when comparing the high arched and flat foot groups. It would be interesting to note if there was a difference in both rearfoot eversion and forefoot dorsiflexion if the heel did not strike the ground first. It may also be plausible for forefoot dorsiflexion to be greater for individuals who landed on the ground with a

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midfoot or forefoot strike. As runners and even walkers may utilise different foot strike patterns (for example, mid or forefoot strikes), it may be relevant that future studies investigate the foot kinematics with these other foot strike patterns.

Conclusions

This study aimed to investigate the association of a static measure of foot posture i.e. FPI scores with dynamic rearfoot eversion and arch flattening (forefoot dorsiflexion) during slow running. When looking at foot posture in groups, the flat foot group exhibited the highest amount of rearfoot eversion followed by the normal arched and high arched groups. The flat foot only exhibited greater forefoot dorsiflexion compared to the high arched group, with no differences found when compared to the normal arched group. Greater rearfoot eversion and forefoot dorsiflexion (arch flattening) was associated with higher FPI scores during slow running, with moderate and small effect sizes respectively. Clinicians can use this information to aid their foot assessment and management of individuals who are recreational runners.

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Figure 1: Marker placements on the participant's lower limb

Figure 2: Segment model of the right foot

Figure 3: Rearfoot eversion range of motion (with 95% confidence levels) of one high arched participant

Figure 4: Forefoot dorsiflexion range of motion (with 95% confidence levels) of one high arched participant

Figure 5: Total rearfoot eversion, forefoot dorsiflexion and the 95% confidence intervals (CI) amongst the three foot posture groups



Figure 1: Marker placements on the participant's lower limb

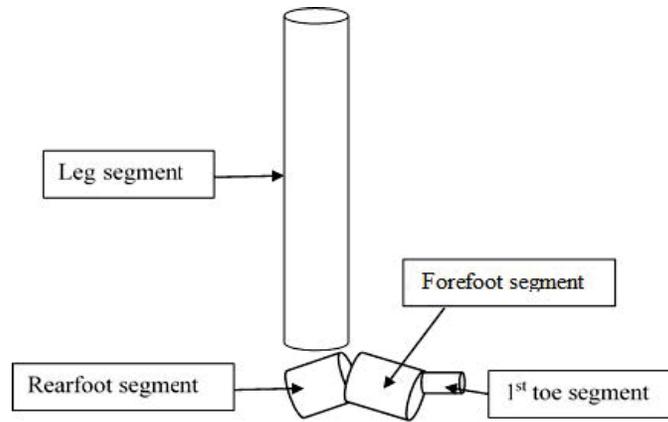


Figure 2: Segment model of the right foot

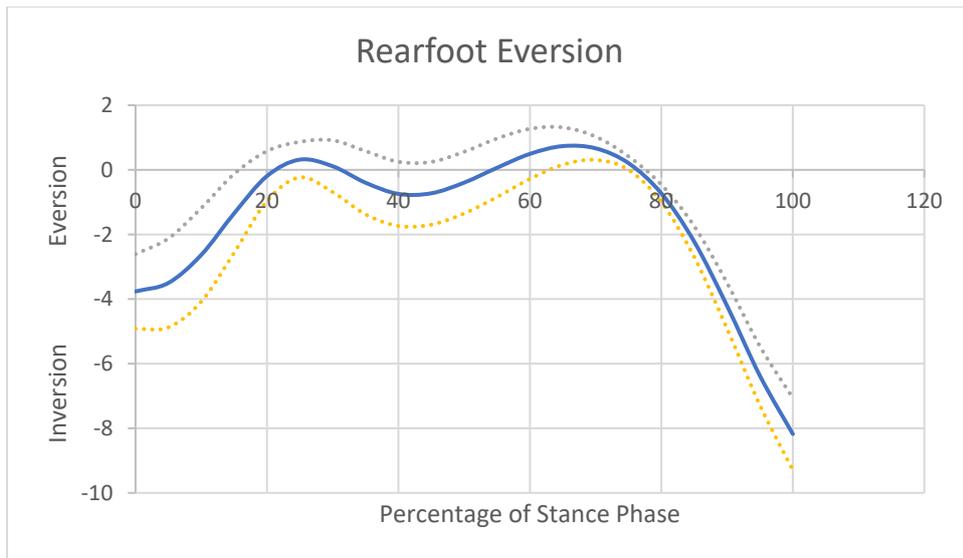


Figure 3 Rearfoot eversion range of motion (with 95% confidence levels) of one participant

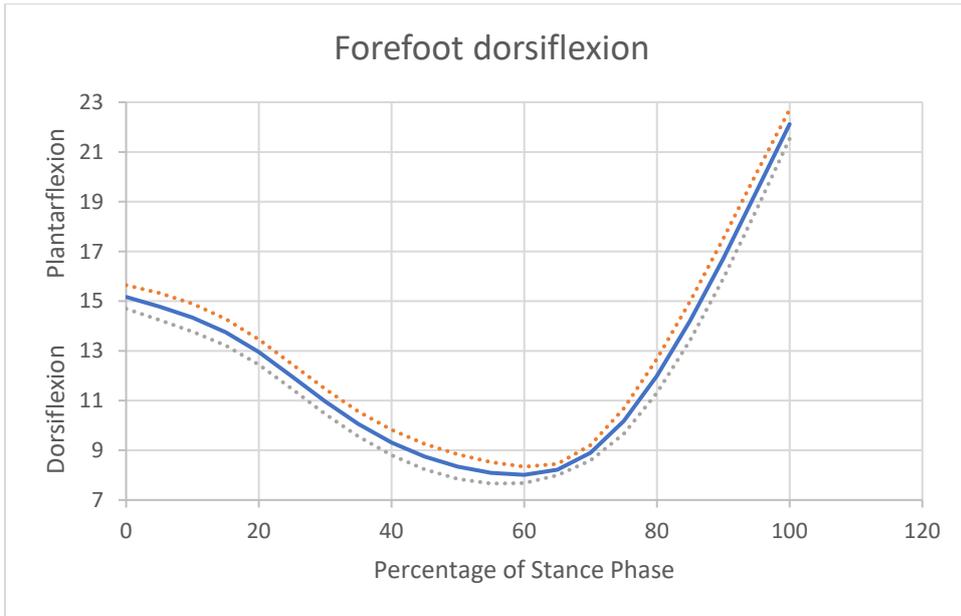


Figure 4 Forefoot dorsiflexion range of motion (with 95% confidence levels) of one participant

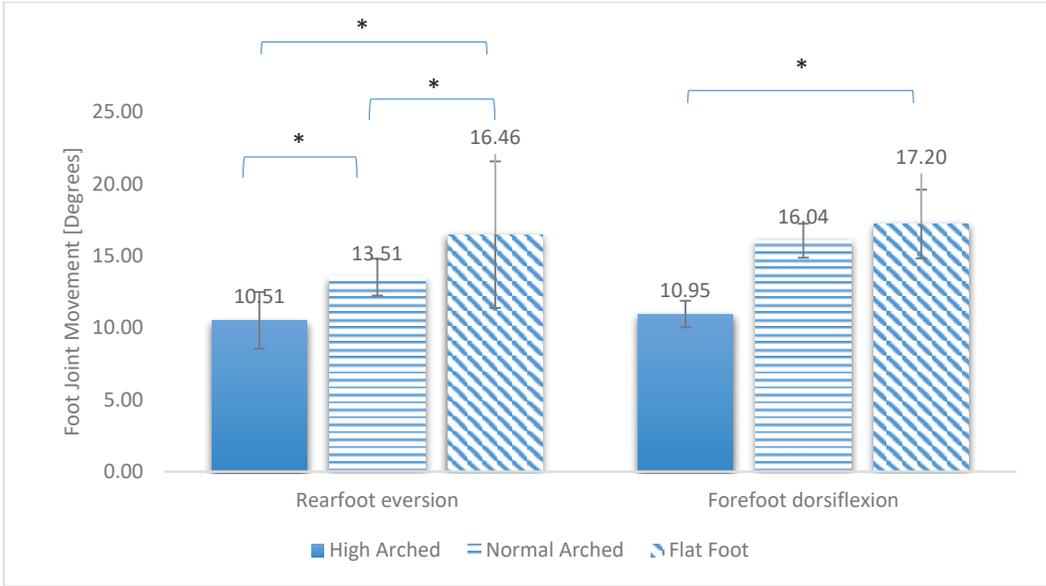


Figure 5: Total rearfoot eversion, forefoot dorsiflexion and the 95% confidence intervals (CI) amongst the three foot structure groups.