

Title: The Influence of Running Shoes on Inter-Segmental Foot Kinematics

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Abstract

The aim of this study was to determine the influence of motion control, neutral and cushioned running shoes upon inter-segmental foot kinematics. Twenty-eight active males completed one testing session, in which they ran in standardised motion control, neutral and cushioned running shoes on a treadmill at a self-selected pace ($2.9 \pm 0.6 \text{m}\cdot\text{s}^{-1}$). Incisions were made within the shoes to enable the motion of the foot to be tracked using a motion analysis system and inter-segmental foot kinematics calculated using the IOR foot model. Discrete parameters associated with midfoot-rearfoot, forefoot-rearfoot, forefoot-midfoot and medial longitudinal arch motion were compared between footwear conditions. Midfoot-rearfoot eversion upon initial contact and peak medial longitudinal arch angles were significantly lower in the motion control shoe compared to the neutral and cushioned shoes. The reductions in midfoot-rearfoot eversion and medial longitudinal arch deformation in the motion control running shoe may be due to increased medial posting and torsional control systems in this shoe. However, these changes in midfoot kinematics may be offset by significant increases in sagittal plane midfoot-rearfoot and forefoot-rearfoot range of motion, particularly during mid-stance.

Key Words

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Introduction

Multi-segmental foot models (MSFM) offer a means of overcoming the limitations with traditional approaches to modelling the foot in three-dimensional motion capture, by providing information on the relative movement of different segments of the foot. Viewing the foot as a single segment disregards the important inter-segmental motion that occurs within the foot. Invasive studies (Lundgren *et al.*, 2008; Wolf *et al.*, 2008, Arndt *et al.*, 2007) have reported movement of up to 17.0°, 17.2° and 16.0° in the sagittal, frontal and transverse planes respectively, at different articulations within the foot, during walking and running. These studies challenge the assumption that the foot can or should be modelled as a single rigid segment.

To date, there has been limited application of a MSFM in the assessment of the shod foot. The few studies (Halstead, Keenan, Chapman & Redmond, 2016; Arndt *et al.*, 2013; Morio, Lake, Gueguen, Roa & Baly, 2009; Elsami, Begon, Farahpour & Allard, 2007) that have applied a MSFM to the assessment of the shod foot have typically used either gait sandals or extreme modification to the shoe, such as the complete removal of the shoes upper to enable the foot to be tracked directly. Removing the entire upper neglects the role this component of the shoe plays in supporting the foot and thus is liable to comprise the function of the shoe. Authors (Shultz & Jenkyn, 2012; Stacoff, Reinschmidt, & Stussi, 1992) have advocated making incisions within the shoe to enable shod foot kinematics to be tracked directly and studies (Langley, Cramp, Morisasa, Nishiwaki & Morrison, 2015; Bishop, Arnold, Fraysse & Thewlis,

2013) have validated the size and number of incisions that can be made within the shoe without significantly altering the structural integrity of shoes. Applying a MSFM to track the motion of the foot within the running shoe would provide a greater understanding of how different shoe design features or types of shoes influence foot motion.

In line with traditional running injury paradigms, running shoes are designed with motion control and cushioning features, which aim to reduce excessive foot motion and the rate and/or magnitude of force application (Davis, 2014). It is common, within the footwear community, for running shoes to be classified based on their design features. Three common types of running shoes on the market are cushioned, neutral and motion control shoes. Cushioned running shoes are designed to enhance force dissipation, motion control shoes are designed to reduce excessive foot motion, whereas neutral shoes include a mixture of motion control and cushioned features (Davis, 2014; ACSM, 2011). Previous studies (Lilley, Stiles & Dixon, 2013; Cheung & Ng, 2007) have demonstrated that motion control shoes reduce RF motion by between 0.9 and 6.5° compared to neutral shoes. However, these studies have used shoe based markers which are a poor indication of the motion of the foot within the shoe (Sinclair et al., 2013a; Stacoff et al., 1992). Based on the discrepancies between the motion of the shoe and the motion of the foot within the shoe, Arnold and Bishop (2013) stated that shoe based markers provide an inappropriate means of estimating in-shoe foot motion due to a lack of validity. Furthermore, the aforementioned shoes differ not only in RF construction but also in the features at the midfoot (MF) and forefoot (FF), and the impact of these differences upon foot motion is unknown. For instance, the

torsion control system and medial posting built into the motion control shoe are likely to influence medial longitudinal arch and MF kinematics. Application of a MSFM to explore the influence of motion control, neutral and cushioned running shoes on inter-segmental foot motion would provide novel information on how these different types of running shoes impact on foot motion, in turn enabling the efficacy of different types of running shoes to be determined. The aim of this study was therefore to determine the influence of motion control, neutral and cushioned running shoes influence inter-segmental foot kinematics.

Methods

Participants

Twenty-eight active males (26 ± 7 years, 1.77 ± 0.05 m, 79 ± 9 kg) were recruited for this study, from local running/sports clubs. Participants reported exercising three to four times per week, which included running two to three times per week on average. Inclusion criteria for the study were that participants were male, 18 – 45 years old, free from cardiovascular illness or musculoskeletal injury at the time of testing. Participant's health status was assessed using the Physical Activity Readiness Questionnaire (PAR-Q). All participants provided written informed consent prior to participating and ethical approval was granted for the study by the Research Ethics Committee of the host institution.

Footwear Conditions

Standardised motion control (ASICS Gel-Forte), neutral (ASICS GT 2000 2) and cushioned (ASICS Gel-Cumulus 15) running shoes were provided by the manufacturer and classified according to the manufacturer's advice. Details regarding the shoe characteristics of each type of shoe are provided in table 1. Four incisions, of 2.5cm diameter, were made within the right shoe to enable the motion of the foot within the shoe to be tracked directly. Incisions were made in the following locations; lateral to the Achilles tendon attachment on the calcaneus, at the navicular tuberosity, and at mid-shaft of the first and fifth metatarsals (Figure 1). Previous work (Langley et al., 2015) has demonstrated that this incision set has minimal impact on the structural integrity of the running shoes.

Procedures

Participants attended one testing session lasting between 1 – 1.5 hours. At the beginning of the session participants undertook a ten minute familiarization period on a Jaeger LE 300 C treadmill (Erich Jaeger GmbH & Co, Wuerzburg, Germany), to reduce kinematic differences between overground and treadmill locomotor patterns (Riley *et al.*, 2008; Lavcanska, Taylor & Schache, 2005). After completing the

familiarization period anatomical and tracking markers were attached to the right foot. Anatomical markers were attached in-line with the Istituti Ortopedici Rizzoli (IOR) foot model (Leardini et al., 2007). The IOR foot model is a four segment MSFM, consisting of shank, RF, MF and FF segments. In accordance with the Calibrated Anatomical Systems Technique (CAST) (Cappozzo, Catani, Croce & Leardini, 1995) triad marker clusters were used to track each segment of the foot during dynamic trials. Anatomical and tracking marker locations for each segment of the MSFM are detailed in table 2. The triad marker cluster design consisted of a base which was attached to the foot using double sided tape and Micropore™ surgical tape and the cluster which was screwed into the base. This design enabled the cluster bases to remain on the foot while the footwear condition was changed, ensuring consistent marker placement between shod conditions. The segment coordinate system for each segment was oriented with the X axis medial to lateral, Y axis posterior to anterior and Z axis distal to proximal. Based on the orientation of the segment coordinate system joint rotations were interpreted as such; X axis dorsi-flexion (+) and plantar-flexion (-), Y axis inversion and eversion, and Z axis adduction and abduction. Joint rotations were calculated using an XYZ Cardan sequence of rotations. Once participants were fully fitted with both anatomical and tracking markers, a static trial was recorded barefoot. This enabled the relevant anatomical reference frames to be calculated for each segment, setting the position and orientation of each segment in relation to the tracking markers. After the static trial was recorded, anatomical markers were removed. During dynamic trials participants ran at a self-selected pace ($2.9 \pm 0.6 \text{m}\cdot\text{s}^{-1}$) and completed three minute long trials in each of the shod conditions (neutral, motion control and cushioned). Data was collected continuously for the final 30 seconds of each trial. The order of testing was randomised to reduce any potential order effects.

An eight camera VICON MX motion analysis system (VICON Motion Systems Ltd., Oxford, England), operating at 200Hz, was used to track the position of retro-reflective markers attached to foot, in line with the model detailed above. Prior to data collection the VICON system was calibrated following the manufacturer's guidelines. Raw marker trajectories were reconstructed, labelled and filtered, using a 10Hz Butterworth filter, within VICON Nexus 1.7.1 (Vicon Motion Systems Ltd., Oxford, England). Gaps, of up to five frames, in marker trajectories were filled using the in-built pattern fill function within VICON Nexus 1.7.1. Processed trials were cropped to five consecutive gait cycles and exported to Visual 3D (C Motion Inc., Leicester, England), where MF-RF, FF-RF, FF-MF and medial longitudinal arch (MLA) motion patterns were calculated.

Gait cycle parameters were identified from the kinematic data (Fellin, Manal & Davis, 2010). Joint angles were averaged over five consecutive gait cycles for each participant and normalised to 100% stance phase duration. Joint angles were normalised to static posture recorded barefoot in a relaxed standing position. A number of discrete angles were pre-selected, in line with the literature (Sinclair, Greenhalgh, Brooks, Edmundson & Hobbs, 2013b; Sinclair, Hobbs, Currigan & Taylor 2013c; Hutchison, Scharfbillig, Uden & Bishop, 2015), to describe the motion pattern of each joint and extracted for statistical analysis. Angles upon initial contact (IC) and toe off (TO) were extracted to determine how the footwear assessed altered the alignment of the foot at the start and end of the stance phase. Peak angles and range

of motion (ROM), defined as the difference between IC and peak angle, were also extracted to explore the influence of the test conditions upon the magnitude of motion reached. ROM during loading response (ROM_{LR}) (0 – 15% stance), mid-stance (ROM_{MS}) (15 – 50%) and propulsion (ROM_{PR}) (50 – 100% stance) were also extracted to provide measures of how footwear influences foot motion during different phases of stance, in line with Hutchison et al., (2015).

Statistical Analysis

Descriptive statistics (mean (standard deviation)) were calculated within Microsoft Excel 2013 (Microsoft, Redmond, WA, USA). All statistical analysis was undertaken in SPSS 20 (IBM, Armonk, NY, USA). Prior to data analysis all data were explored for normal distribution, using a Shapiro-Wilk test. Where data met parametric assumptions, differences between shod conditions were explored using a one-way repeated measures analysis of variance (ANOVA). Where significant main effects were observed, Bonferroni corrected pairwise comparisons were undertaken post-hoc. Where data violated parametric assumptions, differences between shod conditions were explored using Friedman's ANOVA. Where significant main effects were observed, pairwise comparisons were conducted post hoc. Partial eta squared (η^2) was used as an estimate of effect size for the repeated measures ANOVA and Kendall's W (W) was used for Friedman's ANOVA. Effect sizes were interpreted as follows; .1-.24 small, .25-.39, medium and $\geq .4$ large (Portney & Wakins, 1997). The level of significance for this study was set at $p \leq .05$.

Results

Figure 2 displays group average MF-RF, FF-RF, FF-MF motion patterns and figure 3 displays MLAA during the stance phase of running in motion control, neutral and cushioned running shoes. Tables 3-6 present selected discrete parameters associated with MF-RF, FF-RF, FF-MF and MLA kinematics, respectively, when running in each footwear condition.

Midfoot to Rearfoot

In the sagittal plane, a significant ($p = .042$, $W = .11$) main effect was reported for MF-RF ROM, with ROM significantly ($p = .048$) increased when running in the motion control shoe compared to the neutral shoe (Table 3). No significant ($p > .05$) differences in ROM were reported between the cushioned shoe and either the motion control or neutral shoes. Significant main effects were reported for sagittal plane MF-RF ROM_{LR} ($p = .045$, $W = .11$), ROM_{MS} ($p = .014$, $\eta^2 = .15$) and ROM_{PR} ($p = .002$, $W = .22$) between footwear conditions. ROM_{LR} was significantly ($p = .048$) reduced when running in the motion control shoe compared to the cushioned shoe. ROM_{MS} and ROM_{PR} were significantly ($p \leq .005$) reduced when running in the neutral shoe compared to the motion control shoe, and ROM_{PR} was also significantly ($p = .018$)

lower when running in the neutral shoe compared to the cushioned shoe. No other significant main effects were observed for sagittal plane MF-RF kinematic parameters. In the frontal plane, a significant ($p = .003$, $W = .20$) main effect was observed for MF-RF eversion upon IC (Table 3). Pairwise comparisons revealed that the MF was significantly more everted relative to RF upon IC when running in both the cushioned ($p = .015$) and neutral ($p = .008$) shoes compared to the motion control shoe. No significant ($p = 1.00$) difference in MF-RF eversion upon IC was revealed between the neutral and cushioned shoes. No other significant ($p > .05$) main effects were observed for the MF relative to the RF (Table 3).

Forefoot to Rearfoot

In the sagittal plane, a significant ($p = .037$, $W = .12$) main effect was reported for peak FF-RF dorsi-flexion (Table 4). Post hoc analysis revealed that peak FF-RF dorsi-flexion was significantly ($p = .033$) increased when running in the motion control shoe compared to the cushioned shoe. Significant main effects were reported for FF-RF ROM ($p = .002$, $\eta^2 = .21$), ROM_{LR} ($p = .002$, $\eta^2 = .21$), ROM_{MS} ($p = .044$, $\eta^2 = .11$) and ROM_{PR} ($p = .050$, $\eta^2 = .11$). Pairwise comparisons revealed a significant ($p = .003$) reduction in sagittal plane FF-RF ROM when running in the neutral shoe compared to the motion control shoe. ROM_{LR} was significantly lower when running in the neutral shoe compared to both the motion control ($p = .016$) and cushioned ($p = .003$) shoes, with no significant ($p = 1.00$) differences between the motion control and cushioned shoes. ROM_{MS} and ROM_{PR} were higher when wearing the motion control shoe

compared to the neutral and cushioned shoes, however when pairwise comparisons were Bonferroni corrected the differences between conditions were not significant ($p > .05$). No significant ($p > .05$) main effects were reported for FF-RF kinematic parameters in the frontal or transverse planes (Table 4).

Forefoot to Midfoot

No significant ($p > .05$) differences in sagittal or frontal plane FF-MF kinematic parameters were recorded between the three footwear conditions in the sagittal, frontal or transverse planes of motion (Table 5). A significant ($p = .045$, $W = .11$) main effect for transverse plane FF-MF ROM was reported. FF-MF transverse plane ROM was higher in the neutral shoe compared to the cushioned shoe, but no significant ($p > .05$) Bonferroni corrected pairwise comparisons were reported. No other significant differences were reported for FF-MF kinematic parameters in the transverse plane (Table 5).

Medial Longitudinal Arch

A significant ($p = .029$, $\eta^2 = .12$) main effect was observed for MLAA upon IC (Table 6). MLAA upon IC was higher in the motion control shoe compared to both the neutral and cushioned shoes. However, when post hoc analysis with Bonferroni corrections

was undertaken no significant ($p > .05$) differences in MLAA upon IC between the motion control, neutral and cushioned shoes were evident. A significant ($p = .043$, $W = .11$) main effect was observed for peak MLA deformation. Pairwise comparisons revealed a significant ($p = .040$) decrease in peak MLA deformation when running in motion control shoes compared to cushioned shoe. No significant differences in peak MLA deformation were reported between neutral and motion control ($p = 1.00$), or neutral and cushioned shoes ($p = .373$). No other significant ($p > .05$) differences in MLA motion were reported (Table 6).

Discussion

The aim of this study was to determine the influence of motion control, neutral and cushioned running shoes on inter-segmental foot kinematics. Work of this nature has both clinical and sporting implications (Arndt *et al.*, 2013). Clinically, altering inter-segmental foot motion may help to inform strategies for reducing the risk of injury in line with traditional injury paradigms (Arndt *et al.*, 2013; Williams III, McClay & Hamill, 2001). In a sporting context, the findings of studies such as this one may be beneficial for athletes looking for external means of enhancing performance. The findings of the work highlighted that different types of conventional running shoes significantly altered aspects of inter-segmental foot kinematics and while the effect sizes indicate that the reported differences are small, the results are relevant for understanding the impact of footwear on foot biomechanics.

MF-RF eversion upon IC was significantly reduced when running in the motion control shoe compared to both the neutral and cushioned shoes (Table 3). Although no other significant differences in frontal plane MF-RF kinematic parameters were reported, visual assessment of Figure 2 reveals increased MF-RF eversion when running in the neutral and cushioned shoes compared to the motion control shoe. Reducing MF-RF eversion may be beneficial given the link between excessive foot pronation and running related injuries (Chang, Rodrigues, Van Emmerick & Hamill, 2014; Willems *et al.*, 2006). Furthermore, a recent cross sectional study (Chang *et al.*, 2014), reported that individuals with plantar fasciitis demonstrated significantly greater MF-RF eversion during running. As such motion control running shoes, such as those tested within the current study, which reduce MF-RF eversion may help reduce runner's risk of developing plantar fasciitis should prospective studies confirm the relationship between these variables.

Peak MLA deformation was significantly reduced in the motion control shoe compared to the cushioned shoe (Table 6). MLA deformation has previously been used as a measure of foot function (Langley, Cramp & Morrison, 2015; McPoil & Cornwall, 2007), and is associated with RF and MF pronation. Visual assessment of Figure 3 reveals that the MLAA is higher in the motion control running shoe compared to both the neutral and cushioned shoes, especially during loading response and mid-stance. This evidence further supports the impact of motion control running shoes on reducing components of foot motion. Additionally, a significant main effect was observed for the

MLAA upon IC, however Bonferroni corrected post hoc analysis revealed no significant differences between footwear conditions. This may be due to the conservative nature of the Bonferroni correction (Field, 2013). Assessment of the mean data reveals an increase in MLAA upon IC in the motion control shoe compared to the neutral and cushioned shoes.

The reductions in both MF-RF eversion and MLAA when running in the motion control shoe reported within this study are expected based upon the design aims and features of the test shoes (Davis, 2014; Butler, Hamill & Davis, 2007; Asplund & Brown, 2005). The medial posting and torsional control systems built into the motion control running shoe in comparison to the neutral and cushioned shoes may be one factor responsible for reducing MF-RF eversion and MLA deformation when running in this shoe. Support for this is provided by studies (Milani, Schnabel & Hennig, 1995; Perry & Lafortune, 1995) exploring the influence of medial and lateral wedges upon RF kinematics. These studies revealed that increased medial posting resulted in significantly reduced RF eversion. Furthermore, the reduced MF-RF eversion and MLA deformation in the motion control shoe are likely to be inter-related. Shoe design features that reduce MF-RF eversion are liable to reduce the magnitude to which the MLA can deform. However, the significant increase in peak FF-RF dorsiflexion and FF-RF sagittal plane ROM suggest the reduction in frontal plane MF motion may be offset by increased sagittal plane FF motion when running in the motion control shoe.

FF-RF sagittal plane ROM and peak dorsi-flexion were significantly greater when running in the motion control shoe compared to the neutral shoe (Table 4). These findings demonstrate an increase in the flattening of the FF segment of the foot relative to the RF when running in the motion control shoe compared to the neutral and cushioned shoes shoe. The increase in sagittal plane FF-RF flattening may account for the small but insignificant increases in MLA ROM when running in the motion control shoe compared to the neutral shoe. The differences in FF-RF sagittal plane ROM and peak FF-RF dorsi-flexion may be a result of the stiffer and harder soles of the motion control running shoe. Dixon, Collop and Batt (2000) revealed differences in sagittal plane lower limb kinematics when running on surfaces with different cushioning properties, while Gruber, Boyer, Derrick and Hamill, (2014) revealed that the kinematic alterations associated with FF strike running patterns influence force attenuation mechanisms. As such the sagittal plane alterations in FF-RF motion patterns reported within the current work may demonstrate altered force attenuation mechanisms at the foot when running in the stiffer and harder soled motion control running shoe.

In addition to assessing peak angles and range of motion over the entire stance phase we also calculated ranges of motion during loading response, mid-stance and propulsion to better understand how each type of footwear altered foot motion at different times during the stance phase. A reduced ROM during loading response and mid-stance when the foot is pronating would infer a more stable shoe that is better controlling foot motion. During loading response the motion control shoe appears to better control MF-RF dorsi-flexion compared to the cushioned shoe (Table 3). In

contrast, MF-RF sagittal plane ROM_{MS} is significantly increased during the motion control shoe compared to the neutral shoe. The neutral shoe displays significantly reduced MF-RF ROM_{MS} compared to the motion control shoe, and MF-RF ROM_{PR} in comparison to both the motion control and cushioned shoes (Table 4). The reduced peak dorsi-flexion and significantly reduced relative ROM for the MF-RF likely explain these findings.

Significant differences in ROM_{LR}, ROM_{MS} and ROM_{PR} were also reported for the FF relative to the RF in the sagittal plane (Table 5), with ROM_{LR} significantly increased in the motion control shoe compared to the neutral shoe. No significant pairwise comparisons were reported for ROM_{MS} or ROM_{PR} but assessment of the mean data reveals these variables were increased in the motion control shoe compared to the neutral and cushioned shoes. The increase ROM_{PR} in the motion control shoe may be required to counter the increased peak FF-RF dorsi-flexion reported in this footwear condition, to enable the foot to act effectively as a rigid lever for propulsion. Interestingly, all of the significant differences in sub-phase ROM were reported in the sagittal plane. Sagittal plane lower limb kinematics are often linked to force dissipation (Gruber, Boyer, Derrick and Hamill, 2014) and as such increased ROM during loading response and mid-stance may provide increased force attenuation within the foot. Again though even when significant the differences in ROM_{LR}, ROM_{MS} and ROM_{PR} are small in magnitude and effect size.

This work needs to be interpreted in light of its limitations. Due to the differences in running shoe design between manufacturers and models developed by the same

manufacturer, the findings of this study are limited to shoes comparable to those assessed. This in turn limits the external validity of the study, reducing the extent to which the findings can be extrapolated beyond the make and model assessed. The use of a treadmill may be seen as a limitation of the work; however efforts were made to reduce the differences between treadmill and over-ground running patterns. Participants completed a ten minute familiarisation period prior to data collection in line with the literature (Riley *et al.*, 2008; Lavcanska *et al.*, 2005). The analytical approach undertaken within this work focused on the group responses to the different footwear conditions, while this provided information on how the group as a whole responded to the conditions it neglects the inter-individual responses. There were relatively large differences between participants in relation to a number of the parameters assessed within this work, future work should therefore look to explore the characteristics of individuals who respond in similar ways to each of the footwear conditions with a view to determining groups of responders and non-responders.

Conclusions

This study provides new insight into the influence of different types of running shoe upon inter-segmental foot motion, throughout the stance phase of running. Assessment of discrete parameters revealed that the motion control running shoes reduced MF-RF eversion and MLA deformation, whereas these parameters were increased when running in the cushioned shoe. These changes suggest that the motion control shoe influences frontal plane MF kinematics, however these changes

are accompanied by increased sagittal plane MF-RF and FF-RF motion. Significant differences in sagittal plane ROM during loading response, mid-stance and propulsion were reported for MF-RF and FF-RF motion patterns. These changes in ROM highlight the influence of the shoes throughout the gait cycle and may relate to alterations in force attenuation within the foot. Finally, both the magnitude of change and effect size of the differences reported between footwear conditions were small. As such future work is required to determine the influence of these small changes in inter-segmental foot kinematics upon running injury risk.

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Disclosure statement

The authors declare they have no conflict of interested related to this study.

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Figure Headings

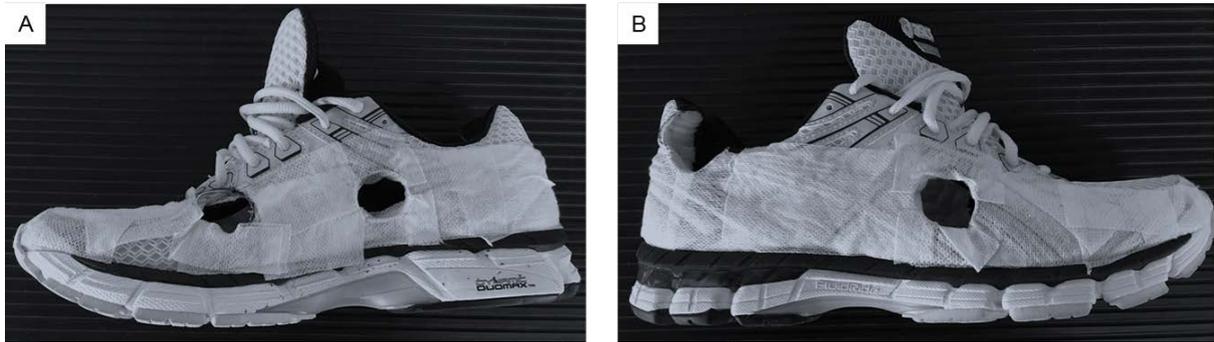


Figure 1. (A) Medial and (B) lateral views of the neutral shoe with 2.5cm diameter incisions visible.

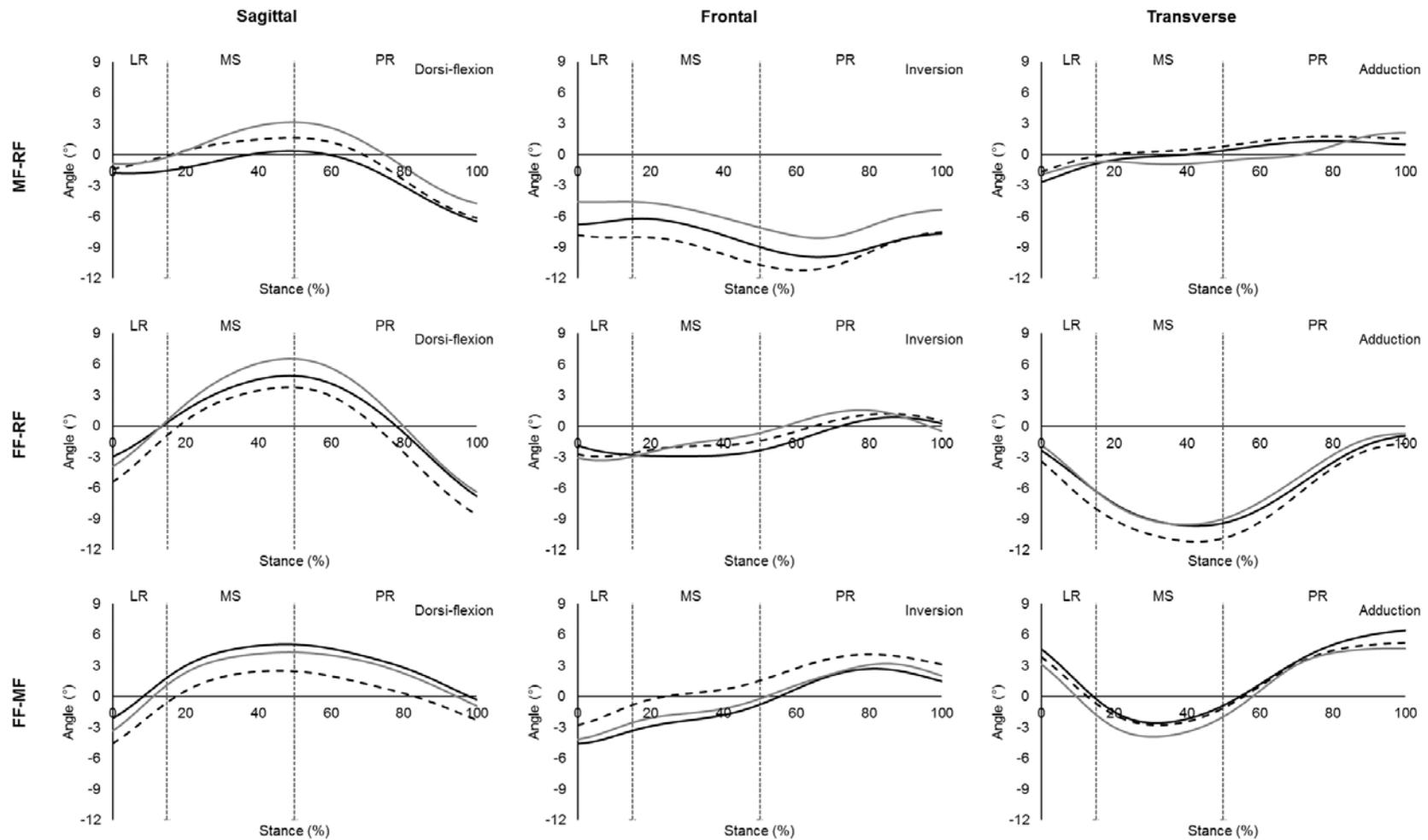


Figure 2. Stance phase midfoot-rearfoot, forefoot-rearfoot and forefoot-midfoot kinematics in motion control (solid grey line), neutral (solid black line) and cushioned (dashed black line) running shoes, averaged across all participants (n = 28). Dashed vertical lines split the figures into loading response (LR), mid-stance (MS) and propulsive (PR) phases

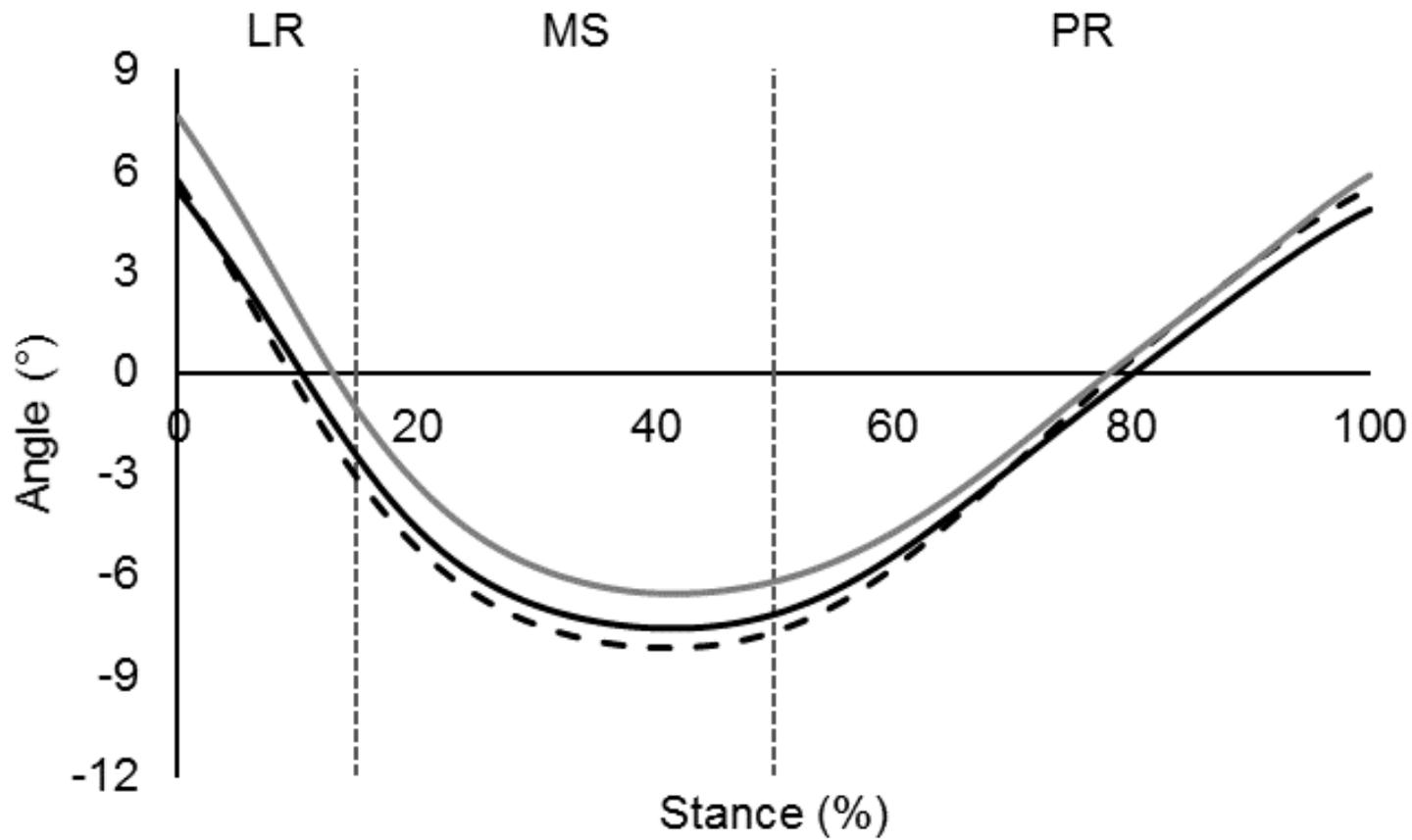


Figure 3. Medial longitudinal arch angles during the stance phase of running when running in motion control (solid grey line), neutral (solid black line) and cushioned (dashed black line) running shoes, averaged across all participants (n = 28) . Dashed vertical lines split the figures into loading response (LR), mid-stance (MS) and propulsive (PR) phases

Tables and Headings

Table 1. Selected characteristics of the motion control, neutral and cushioned running shoes

	Motion Control	Neutral	Cushioned
Mass (g)	377.1	311.9	328.9
Heel Height (mm)	39.0	33.7	36.8
Forefoot Height (mm)	27.3	24.6	25.9
Forefoot to Rearfoot Drop (mm)	11.7	9.1	10.9
Rearfoot Cushioning [†]	23.0	91.0	71.0
Forefoot Cushioning [†]	34.0	91.0	70.0
Stiffness [†]	72.0	44.0	63.0
Stability Features [†]	87.0	70.0	43.0

NOTE: All of the information contained within the table is taken from Runners' World (2015a, b & c)

[†]Ranking score from 1 to 100 determined in testing conducted by Runners' World (2015a, b & c); higher scores for cushioning indicate softer running shoes as determined by impact testing, higher scores for stiffness indicate stiffer shoes determined by calculating the amount of force required to mechanically bend the shoe to 45° and a higher score for stability features indicates a higher prevalence of motion control features within the shoe

Table 2. Anatomical and tracking marker locations for the MSFM used within this study

Segment	Anatomical Marker	Tracking Marker Cluster
Rearfoot	Centre of calcaneus at height of Achilles tendon attachment Sustentaculum tali Peroneal tubercle	Lateral to Achilles tendon attachment
Midfoot	Navicular tuberosity 1 st metatarsal base 2 nd metatarsal base 5 th metatarsal base	Navicular tuberosity
Forefoot	1 st metatarsal head 2 nd metatarsal head 5 th metatarsal head 1 st metatarsal base 2 nd metatarsal base 5 th metatarsal base	Midshaft of the 5 th metatarsal

Table 3. Comparison of midfoot to rearfoot kinematic parameters (mean (SD)) in motion control, neutral and cushioned running shoes. *p* value obtained from one way ANOVA, ‡ *p* value obtained from Friedman's ANOVA

	Motion Control	Neutral	Cushioned	<i>p</i>
X (+ = Dorsi-/ - = Plantar)				
Angle at IC (°)	-0.9 (10.0)	-2.0 (9.6)	-1.4 (10.4)	.752
Angle at TO (°)	-4.7 (9.5)	-6.6 (9.4)	-6.1 (11.3)	.423
Peak DF (°)	4.2 (10.1)	1.4 (9.4)	3.2 (10.6)	.211
Relative ROM (°)	5.1 (3.2)	3.4 (2.9)*	4.6 (3.5)	.042‡
ROM _{LR} (°)	1.7 (1.9)	1.9 (1.3)	2.6 (2.2)*	.045‡
ROM _{MS} (°)	4.1 (1.7)	3.0 (1.6)*	3.2 (1.7)	.014
ROM _{PR} (°)	8.8 (3.8)	7.5 (4.9)*	8.6 (4.0)†	.002‡
Y (+ = Inversion/ - = Eversion)				
Angle at IC (°)	-4.6 (5.5)	-6.9 (6.1)*	-7.8 (6.9)†	.003‡
Angle at TO (°)	-5.4 (6.8)	-7.8 (7.5)	-7.5 (7.9)	.123
Peak Eversion (°)	10.6 (6.0)	11.9 (6.3)	13.2 (7.6)	.096
Relative ROM (°)	6.0 (3.6)	5.0 (4.1)	5.4 (3.5)	.298
ROM _{LR} (°)	3.1 (1.9)	3.3 (2.3)	3.1 (2.4)	.921‡
ROM _{MS} (°)	4.7 (3.1)	4.8 (4.3)	4.0 (3.6)	.218‡
ROM _{PR} (°)	6.0 (3.6)	5.1 (2.8)	6.5 (3.7)	.057‡
Z (+ = Adduction/ - = Abduction)				
Angle at IC (°)	-1.9 (5.8)	-3.0 (7.1)	-1.7 (6.2)	.273
Angle at TO (°)	2.1 (5.6)	0.7 (6.0)	1.6 (5.7)	.200
Peak Adduction (°)	4.1 (4.9)	3.8 (7.2)	4.6 (6.7)	.720
Relative ROM (°)	6.1 (4.3)	6.8 (5.9)	6.2 (5.6)	.247‡
ROM _{LR} (°)	3.5 (3.3)	3.6 (2.9)	3.6 (3.3)	.841‡
ROM _{MS} (°)	3.4 (1.9)	3.7 (2.9)	2.9 (2.2)	.243‡
ROM _{PR} (°)	5.6 (4.1)	4.9 (3.8)	5.5 (4.4)	.082‡

* Significantly different to motion control † Significantly different to neutral

Table 4. Comparison of forefoot to rearfoot kinematic parameters (mean (SD)) in motion control, neutral and cushioned running shoes. *p* value obtained from one way ANOVA, ‡ *p* value obtained from Friedman's ANOVA

	Motion Control	Neutral	Cushioned	<i>p</i>
X (+ = Dorsi-/ - = Plantar)				
Angle at IC (°)	-3.9 (8.1)	-3.0 (8.7)	-5.4 (8.5)	.166‡
Angle at TO (°)	-6.4 (10.4)	-6.4 (9.8)	-8.6 (10.4)	.113‡
Peak DF (°)	7.6 (8.1)	6.0 (8.0)	4.7 (8.7)*	.037‡
Relative ROM (°)	11.5 (4.9)	9.0 (4.0)*	10.2 (4.2)	.002
ROM _{LR} (°)	4.8 (2.7)	3.6 (1.9)*	4.8 (1.9)†	.002
ROM _{MS} (°)	6.4 (2.8)	5.5 (2.4)	5.2 (2.7)	.044
ROM _{PR} (°)	13.6 (5.1)	12.0 (5.7)	12.9 (5.0)	.050
Y (+ = Inversion/ - = Eversion)				
Angle at IC (°)	-3.1 (6.4)	-1.9 (7.0)	-2.7 (7.1)	.573
Angle at TO (°)	-0.5 (4.9)	0.2 (5.7)	2.6 (6.9)	.482
Peak Eversion (°)	5.6 (5.2)	5.2 (7.2)	4.9 (7.0)	.841
Relative ROM (°)	2.5 (2.8)	3.3 (4.0)	2.2 (3.2)	.069‡
ROM _{LR} (°)	2.6 (1.9)	2.7 (2.0)	2.3 (1.6)	.837‡
ROM _{MS} (°)	3.3 (2.4)	3.0 (1.8)	2.8 (1.9)	.179‡
ROM _{PR} (°)	5.4 (2.5)	5.0 (3.7)	4.9 (3.4)	.063‡
Z (+ = Adduction/ - = Abduction)				
Angle at IC (°)	-1.8 (7.2)	-2.0 (8.2)	-3.4 (7.0)	.060‡
Angle at TO (°)	-0.7 (8.2)	-0.9 (9.5)	-1.7 (9.0)	.752‡
Peak Abduction (°)	-10.8 (6.1)	-10.2 (5.8)	-12.2 (6.0)	.547‡
Relative ROM (°)	9.0 (4.3)	8.2 (5.4)	8.8 (4.7)	.526
ROM _{LR} (°)	5.0 (2.8)	4.7 (2.6)	5.1 (2.8)	.565‡
ROM _{MS} (°)	4.7 (3.0)	4.4 (4.7)	4.3 (3.6)	.070‡
ROM _{PR} (°)	9.2 (6.6)	9.2 (6.1)	9.7 (7.2)	.243‡

* Significantly different to motion control † Significantly different to neutral

Table 5. Comparison of forefoot to midfoot kinematic parameters (mean (SD)) in motion control, neutral and cushioned running shoes. *p* value obtained from one way ANOVA, ‡ *p* value obtained from Friedman's ANOVA

	Motion Control	Neutral	Cushioned	<i>p</i>
X (+ = Dorsi-/ - = Plantar)				
Angle at IC (°)	-3.4 (11.5)	-2.0 (11.2)	-4.6 (10.7)	.407
Angle at TO (°)	-0.9 (10.7)	0.1 (11.0)	-2.3 (10.8)	.383
Peak DF (°)	5.1 (11.1)	5.9 (10.2)	3.3 (10.3)	.333
Relative ROM (°)	8.5 (3.5)	7.9 (3.4)	7.8 (3.0)	.313
ROM _{LR} (°)	4.5 (2.5)	4.0 (2.0)	4.0 (2.1)	.144‡
ROM _{MS} (°)	3.3 (1.9)	3.4 (2.0)	3.2 (1.6)	.364‡
ROM _{PR} (°)	5.7 (3.3)	5.6 (2.4)	5.3 (2.9)	.612
Y (+ = Inversion/ - = Eversion)				
Angle at IC (°)	-4.1 (6.6)	-5.0 (8.9)	-2.8 (7.2)	.051
Angle at TO (°)	2.0 (6.9)	1.1 (9.2)	3.1 (8.9)	.125
Peak Inversion (°)	4.0 (6.5)	2.9 (9.2)	5.3 (8.0)	.051
Relative ROM (°)	8.1 (3.7)	7.9 (4.2)	8.0 (3.6)	.179‡
ROM _{LR} (°)	2.8 (2.1)	2.1 (1.4)	2.6 (1.8)	.055‡
ROM _{MS} (°)	2.6 (1.5)	2.7 (1.7)	2.7 (1.6)	.484‡
ROM _{PR} (°)	5.0 (2.8)	4.3 (2.2)	4.6 (2.7)	.679‡
Z (+ = Adduction/ - = Abduction)				
Angle at IC (°)	3.1 (7.1)	4.6 (8.7)	3.9 (6.8)	.259
Angle at TO (°)	4.6 (6.4)	6.6 (7.6)	5.2 (6.8)	.071
Peak Abduction (°)	4.4 (7.6)	2.7 (7.2)	3.4 (6.7)	.282
Relative ROM (°)	7.5 (3.9)	7.7 (4.4)	7.3 (5.5)	.045
ROM _{LR} (°)	5.0 (3.2)	5.0 (3.0)	5.0 (3.8)	.437‡
ROM _{MS} (°)	3.6 (1.8)	3.6 (2.4)	2.9 (1.7)	.257
ROM _{PR} (°)	7.5 (4.1)	7.5 (3.7)	7.4 (4.7)	.986

* Significantly different to motion control † Significantly different to neutral

Table 6. Comparison of medial longitudinal arch kinematic parameters (mean (SD)) in motion control, neutral and cushioned running shoes. *p* value obtained from one way ANOVA, ‡ *p* value obtained from Friedman's ANOVA

	Motion Control	Neutral	Cushioned	<i>p</i>
Angle at initial contact (°)	07.6 (6.2)	05.4 (7.5)	05.7 (6.5)	.03
Angle at toe off (°)	05.9 (7.0)	04.9 (7.07)	05.5 (8.1)	.37‡
Peak deformation (°)	-7.0 (5.4)	-8.0 (6.3)	-8.5 (5.6)*	.04‡
Relative ROM (°)	14.6 (5.0)	13.6 (4.6)	14.1 (4.5)	.35
ROM _{LR} (°)	8.7 (3.6)	8.0 (2.7)	8.8 (3.0)	.21
ROM _{MS} (°)	5.4 (2.7)	5.2 (2.2)	4.8 (2.4)	.21‡
ROM _{PR} (°)	12.1 (3.7)	11.9 (4.3)	13.1 (4.2)	.10

* Significantly different to motion control † Significantly different to neutral