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The Influence of Motion Control, Neutral and Cushioned Running Shoes on Lower Limb Kinematics

Abstract

To-date there is a paucity of information about how different types of conventional running shoes influence lower limb kinematics. The aim of the study was to determine the influence of motion control, neutral and cushioned running shoes upon lower limb kinematics. Twenty-eight active males completed one test session running in standardised motion control, neutral and cushioned running shoes, on a treadmill at a self-selected pace (2.9 ± 0.6 m.s^{-1}). Kinematic data were collected using a VICON motion analysis system with hip, knee and ankle joint angles calculated. Discrete parameters associated with stance phase kinematics were compared between footwear conditions. Significant ($p < .05$) differences in knee flexion and internal rotation at toe off, and knee adduction range of motion were reported between footwear conditions. Significant ($p < .05$) differences in ankle joint dorsi-flexion and adduction upon initial contact, peak dorsi-flexion, eversion and abduction, and inversion at toe off were reported between footwear conditions. The influence of motion control, neutral and cushioned running shoes on joint function dissipates moving proximally, with larger changes reported at the ankle compared to knee and hip joints. While significant differences were reported between footwear conditions, these changes were of a small magnitude and effect size.

Key Words: footwear, hip, knee, ankle

Word Count: 2,934 words

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Introduction

Traditional running-injury paradigms have been challenged within the literature[1], yet still underpin running shoe design. As such, running shoes are still designed with stability and cushioning features which are thought to influence the rate and/or magnitude of foot motion and impact loading[2,3]. Running shoes are often categorised based upon their design features and may broadly be classified as trail, performance, minimalist or conventional running shoes[4-6]. Conventional running shoes are often further sub-classified based upon their specific stability and cushioning features, in to motion control, neutral and cushioned categories[4-6]. Currently no objective method for this sub-classification exists and as such running shoes are often classified based upon manufacturer recommendations. Furthermore, these terms are by no means uniform with different manufactures, retailers or publications often using neutral/stability or cushioned/neutral interchangeably[4-8]. For clarity the terms motion control, neutral and cushioned will be used exclusively throughout this manuscript. Motion control running shoes aim to reduce the magnitude and/or rate of pronation with a view to enhancing the propulsive efficiency of the foot, in comparison to neutral and cushioned shoes[6,9,10]. In contrast, cushioned running shoes aim to reduce the magnitude and/or rate of impact loading, and increase foot motion relative to neutral and motion control running shoes[6,9,10]. Neutral running shoes combine a number of motion control and cushioning features with a view to providing some additional stability compared to cushioned running shoes, and greater force attenuation than motion control running shoes[6,9,10].

Studies[11,12] have demonstrated that motion control running shoes reduce rearfoot eversion compared to neutral shoes. However, as is common within footwear biomechanics, these studies[11,12] placed markers on the shoe. Discrepancies between the motion of the foot and the shoe have been reported[13-15] and as such, the findings of studies using shoe based markers

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should be interpreted with caution. The only study[10] known to the authors comparing in-shoe foot motion, when running in motion control and cushioned running shoes, found no significant differences in rearfoot eversion. Further work is required to explore the influence of motion control, neutral and cushioned running shoes on in-shoe foot motion.

Assessment of rearfoot eversion has been widely reported over the past 40 years[11,12,17-19] as a measure of how footwear influences foot motion. This approach offers limited understanding of the influence footwear modifications may have upon the sagittal and transverse plane motions of the foot, or upon more proximal joints. The assessment of how footwear influences lower limb kinematics may help to elucidate mechanisms by which injury risk can be mitigated; as hip and knee joint kinematics have been linked to the development of overuse running injuries[20-23]. Two studies[10,24] have demonstrated that motion control running shoes reduce internal tibial rotation compared to cushioned or neutral running shoes, respectively. While Hutchison et al[25] reported significant reductions in internal knee rotation when running in motion control shoes compared to neutral shoes. These findings highlight that motion control, neutral and cushioned running shoes have the potential to influence more proximal joint kinematics. However, there is a lack of published data relating to the influence of these types of commercially available running shoes upon three dimensional (3D) lower limb kinematics. The aim of this study was to determine the influence of motion control, neutral and cushioned running shoes on lower limb kinematics. Three hypotheses were tested; (1) lower limb kinematics will differ between motion control, neutral and cushioned running shoes, (2) motion control running shoes will reduce the magnitude of ankle joint eversion compared to neutral and cushioned running shoes, and (3) cushioned running shoes will increase the magnitude of ankle joint eversion compared to neutral and motion control running shoes.

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Methods

Based upon an *a priori* sample size calculation, using the method of Eng[26] and the data of Cheung and Ng[11], 28 active males (26 ± 7 years, 1.77 ± 0.05 m, 79 ± 9 kg) were recruited for this study. Participants were free from injury and/or illness at the time of testing, as determined by a health screening questionnaire. On average participants reported exercising three to four times per week, including running two to three times per week. Foot strike pattern was not controlled within the study to enhance the generalisability of the findings; 19 participants were rearfoot, 6 midfoot and 3 forefoot strikers. Ethical approval was granted for this study by the Research Ethics Committee of the host institution and written informed consent was provided by all participants prior to testing.

Participants attended one test session lasting between 1 – 1.5 hours. At the beginning of the session, participants undertook a 10 minute familiarization period on a Jaeger LE 300 C treadmill (Erich Jaeger GmBH & Co, Wuerzburg, Germany), to minimise kinematic differences between overground and treadmill conditions[27,28]. After the familiarization period, anatomical and tracking markers were attached in line with a four segment lower limb model (described below). 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 and lower limb. Prior to data collection, the VICON system was calibrated following the manufacturer's guidelines.

To define the foot, shank, thigh and pelvis, 14mm retro-reflective markers were attached to the right limb at the following locations; first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, and bilaterally to the anterior and posterior superior iliac spines. In accordance with the calibrated anatomical system technique[29], marker clusters were used to track each segment during dynamic trials. The foot was tracked

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by a triad marker cluster attached to the posterior-lateral aspect of the calcaneus at the height of the Achilles tendon attachment (Figure 1). To enable the marker cluster to be attached directly to the foot, a 25 mm incision was made within each shoe[30,31]. Four incisions were made within the shoe in total, as this study was part of a larger project which also explored inter-segmental foot kinematics. The incision set was found to have minimal influence upon the running shoes structural integrity[31]. The thigh and shank were tracked by rigid clusters, consisting of four non-collinear markers, located on the distal-lateral aspect of the segment. The pelvis was tracked by a rigid cluster of four non-collinear markers attached to the proximal-posterior aspect of the segment. Once participants were fully fitted with both anatomical and tracking markers a single, static trial was recorded, in a barefoot condition. This enabled the relevant anatomical reference frames to be calculated for each segment. After the static trial was recorded anatomical markers were removed.

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Participants ran at a self-selected pace (2.9 ± 0.6 $m.s^{-1}$) and completed three minute trials in each of the shod conditions; motion control, neutral and cushioned. Data were collected continuously for the final 30 seconds of each trial. The order of testing was randomised to reduce potential order effects. Footwear was standardised using running shoes provided by the manufacturer and classified according to the manufacturer's advice; motion control (ASICS Gel-Forte), neutral (ASICS GT 2000 2) and cushioned (ASICS Gel-Cumulus 15). Details of the design characteristics of each footwear condition are provided in table 1.

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 3D hip, knee and ankle joint kinematics were calculated. Gait cycle parameters were identified from the kinematic data[32]. Joint angles were averaged and time normalised to 100 % stance phase duration. All joint angles were normalised for each participant to their static posture recorded barefoot in a relaxed standing position, enabling differences in absolute joint angles to be compared between footwear conditions[33]. Discrete angles were pre-selected, in line with the literature[34], to describe the motion pattern of each joint and extracted for statistical analysis. The discrete variables used to describe stance phase kinematics were angles at initial contact (IC) and toe off (TO), joint range of motion (ROM), peak angles and time to peak angle.

Descriptive statistics (mean (standard deviation)) were calculated within Microsoft Excel 2013 (Microsoft, Redmond, WA, USA). 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, post hoc pairwise comparisons were undertaken. 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; small effect ≥ .10, moderate ≥ .30 and large ≥ .50[35]. The level of significance for main effect within the study was set at $p < .05$, with post hoc comparisons Bonferroni corrected.

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Results

Significant main effects were observed for ankle joint dorsi-flexion upon IC (p = .01, W = .16) and peak ankle dorsi-flexion in stance (p = .02, W = .14) (Table 2, Figure 2). The ankle was significantly more dorsi-flexed upon IC by 2.4° and 3.3° when running in the neutral shoe compared to the motion control (p = .02) and cushioned shoes (p = .03), respectively. Peak ankle joint dorsi-flexion was significantly increased by 2.6° when running in the neutral shoe compared to the cushioned shoe (p = .02). In the frontal plane, significant main effects were observed for ankle joint inversion at TO (p = .05, η^2= .11) and peak ankle joint eversion (p = .04, W = .12). The ankle was significantly more inverted at TO by 1° when running in the neutral shoe compared to the motion control shoe (p = .04), and peak ankle joint eversion was significantly greater by 0.2° in the motion control shoe compared to the cushioned shoe (p = .05). Significant main effects were reported for ankle joint adduction upon IC (p = .03, η^2= .12) and peak ankle joint abduction (p = .01, η^2= .15). The ankle joint was significantly (p = .03) more adducted upon IC when running in the neutral shoe compared to the motion control shoe by 1.4°. Peak ankle joint abduction was significantly (p = .02) greater when running in the motion control shoe compared to the neutral shoe by 1.4°.

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In the sagittal plane at the knee joint, a significant main effect (p = .04, η^2= .17) was reported for knee flexion upon TO (Table 3, Figure 2). The knee was significantly (p = .03) more flexed at TO by 1.1° when running in the neutral shoe compared to the cushioned shoe. A significant main effect (p = .02, W = .14) for adduction ROM was found. Knee adduction ROM was significantly (p = .02) increased in the neutral shoe compared to the cushioned shoe by 0.4°. In the transverse plane, a significant main effect (p = .04, W = .12) was observed for the magnitude of knee internal rotation at TO. The knee was significantly (p = .05) more internally rotated at TO by 0.5° in the motion control shoe compared to the cushioned shoe.

No significant (*p* > .05) differences in hip joint kinematic parameters were recorded between footwear conditions (Table 4, Figure 2).

Discussion

This study examined the impact of motion control, neutral and cushioned running shoes on 3D lower limb kinematics. The findings of this study support hypotheses one with significant differences reported in both knee and ankle joint movement patterns between footwear conditions (Tables 2 & 3). However, these significant differences are small in terms of both magnitude (≤ 3.3°) and effect size (≤ .17), and are below the reported minimal detectable difference (3-6°) for lower limb kinematics during running[36]. As such the significant changes must be interpreted with caution.

The assessment of hip, knee and ankle joint motion within this study provides a more comprehensive insight into how different types of footwear influence lower limb kinematics, in comparison to single joint assessments typically reported within the literature[11,24,25]. Statistically significant differences in knee and ankle joint movement patterns, that would be missed by traditional assessments of ankle joint eversion alone, were identified within this study. Furthermore, changes in knee joint kinematics, across all three planes, were reported which further highlight the efficacy of different types of conventional running shoes to influence motion patterns higher up the kinematic chain. The magnitude of change between footwear conditions reduced more proximally within the kinematic chain. A finding that is supported by Lilley et al[12]. Additional work undertaken by the authors of this study further supports the suggestion that the influence of running shoes upon joint kinematics reduces as you move proximally up the kinematic chain, with changes of a larger magnitude reported for

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parameters associated with inter-segmental foot kinematics for the same participants running in the same footwear conditions[37,38]. As such footwear appears to offer a means of altering foot or ankle joint motion to a greater extent than the movements of the knee or the hip, with the findings of this study suggesting different types of conventional running shoes have little influence on hip joint kinematics.

Peak ankle eversion was greater when running in the motion control shoe compared to the cushioned shoe, however both the magnitude of change (0.2°) and the effect size ($W = .12$) were small (Table 2). This finding contrasts with what would be expected from the design aims of each shoe and the previous literature[11,12], and rejects hypotheses two and three. Studies[11,12] using shoe-based markers have reported significant reductions in peak RF eversion of between 0.9° and 6.5° when running in motion control shoes compared to neutral shoes. In contrast, Butler et al[10] reported no significant differences in in-shoe foot motion between motion control and cushioned running shoes, suggesting small differences between conditions, however no data was reported by the authors. The disparity between the studies using shoe based markers[11,12] and those tracking in-shoe foot motion, such as this one, is important. The existing literature suggests that peak shoe eversion is lower in motion control shoes compared to neutral shoes, potentially due to the more rigid heel counter. However, the reduction in peak shoe eversion does not appear to be replicated by the motion of the foot within the shoe. This is supported by Van Gheluwe, et al[39] who reported larger discrepancies between in-shoe foot motion and the motion of the shoe with more rigid heel counters, such as those built in to the motion control shoe. It should be noted at this time that the lack of consistency in running shoe classification and design features across studies and manufacturers may also explain some of the disparity between studies.

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Significant differences between footwear conditions were also reported in the sagittal and transverse planes at the ankle joint (Table 2). Running in the neutral shoe was associated with significantly increased ankle joint dorsiflexion upon IC and peak dorsiflexion. These changes in sagittal plane kinematics are likely due to the decreased rearfoot to forefoot drop of the neutral shoe (Table 1), placing the foot in a more dorsiflexed position compared to the motion control and cushioned shoes. In the transverse plane, ankle abduction upon IC and peak abduction were significantly greater when running in the motion control shoe compared to the neutral shoe (Table 2). Visual assessment of Figure 2 reveals that the foot is in a more abducted position throughout the entire stance phase when running in the motion control shoe compared to the neutral and cushioned shoes. Closer inspection of the motion patterns reveals that the difference between the three footwear conditions reduces as the stance phase progresses. As such it is speculated that differences in the construction of the rearfoot and midfoot sections of the shoe are liable to account for differences in transverse plane ankle joint motion between footwear conditions.

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There are a number of limitations that must be acknowledged. The use of a single model and manufacturer for each type of shoe may limit the ability to extrapolate the findings of this study beyond running shoes highly similar to those assessed, due to differences in shoe construction between models/manufacturers. The lack of any mechanical testing to quantify the properties of the respective midsoles of each footwear condition further limits the ability to compare to alternative shoe models. However, previous studies[11,12] have not provided this information. Additionally, the lack of a prolonged habituation period to each footwear condition may mean that the findings represent only the acute adaptations to each type of running shoe.

The findings of this study demonstrate that different types of conventional running shoes significantly influence knee and ankle joint kinematics during the stance phase of running gait, thus supporting hypotheses one. However, while there are significant differences between the motion control, neutral and cushioned running shoes the magnitude of change (≤ 3.3°) and effect sizes (≤ .17) were small. Surprisingly, based upon the findings of previous studies[11,12] and the design aims of the respective shoes, motion control shoes did not reduce peak ankle joint eversion. The discrepancies between the findings of this study and the literature may be explained by the assessment of in-shoe foot motion, within the present work. This finding also questions the recommendation of motion control running shoes with a view to reducing the magnitude of foot eversion with a view to reducing injury risk.

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Tables and Legends

Table 1. Design characteristics of the motion control, neutral and cushioned shoes used within this study

	Motion Control	Neutral	Cushioned
Weight (g)	377	312	329
Forefoot Height (mm)	27	25	26
Rearfoot Height (mm)	39	34	37
Heel-Toe Drop (mm)	12	9	11
Impact Guidance System	X	X	X
Guidance trusstic system			X
Reinforced guidance trusstic system	X	X	
Rearfoot Gel Cushioning System	X	X	X
Forefoot Gel Cushioning System	X	X	X
Duomax Support System	X	X	
Triple density midsole	X		
FluidRide EVA Midsole		X	
Guidance Line	X	X	X
SpEVA 45 lasting			X
SpEVA 55 lasting		X	
SpEVA 65 Lasting	X		
Broader Sole Plate	X		
Heel Counter	X	X	X
Heel Counter Reinforcement	X		
Sotyle EVA midsole	X		X

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Table 2. Comparison of ankle joint kinematic parameters (mean (SD)) in motion control, neutral and cushioned running shoes

	Motion Control	Neutral	Cushioned
X (+ = Dorsi-/ - = Plantar)			
Angle at initial contact (°)	-2.8 (6.2)	-0.4 (7.4)*	-3.7 (8.9)†
Angle at toe off (°)	-21.6 (9.3)	-20.1 (8.7)	-23.3 (11.5)
Range of motion (°)	37.6 (7.7)	37.9 (7.7)	38.5 (7.7)
Peak dorsi-flexion (°)	16.0 (5.6)	17.8 (7.8)	15.2 (8.0)†
Time to peak dorsi-flexion (sec)	0.11 (0.02)	0.11 (0.02)	0.11 (0.02)
Y (+ = Inversion/ - = Eversion)			
Angle at initial contact (°)	1.5 (3.8)	1.6 (4.4)	1.9 (4.8)
Angle at toe off (°)	4.5 (4.8)	5.5 (5.0)*	4.8 (5.9)
Range of motion (°)	12.4 (3.0)	12.9 (3.2)	12.6 (3.5)
Peak eversion (°)	-7.7 (4.2)	-7.2 (4.6)	-7.5 (6.0)*
Time to peak eversion (sec)	0.07 (0.02)	0.08 (0.03)	0.07 (0.02)
Z (+ = Adduction/ - = Abduction)			
Angle at initial contact (°)	0.3 (3.9)	1.7 (4.3)*	1.7 (5.0)
Angle at toe off (°)	-1.0 (4.9)	-0.2 (5.0)	-0.1 (5.6)
Range of motion (°)	7.7 (2.9)	7.6 (3.6)	7.7 (3.6)
Peak abduction (°)	-5.1 (3.8)	-3.8 (4.5)*	-3.8 (4.8)
Time to peak abduction (sec)	0.06 (0.05)	0.11 (0.09)	0.08 (0.08)

* Significantly different to motion control

† Significantly different to neutral

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Table 3. Comparison of knee joint kinematic parameters (mean (SD)) in motion control, neutral and cushioned running shoes

	Motion Control	Neutral	Cushioned
X (+ = Flexion/ - = Extension)			
Angle at initial contact (°)	15.1 (7.9)	16.0 (8.2)	15.4 (6.5)
Angle at toe off (°)	13.7 (5.2)	14.1 (5.3)	13.0 (5.7)[†]
Range of motion (°)	24.7 (3.8)	24.0 (4.2)	24.2 (4.5)
Peak flexion (°)	36.7 (6.5)	37.0 (6.7)	36.4 (6.5)
Time to peak flexion (sec)	0.09 (0.01)	0.08 (0.02)	0.09 (0.01)
Y (+ = Adduction/ - = Abduction)			
Angle at initial contact (°)	-0.2 (3.5)	-0.1 (3.6)	-0.1 (3.1)
Angle at toe off (°)	0.3 (3.5)	0.4 (3.6)	0.5 (3.5)
Range of motion (°)	4.3 (1.9)	4.6 (2.3)	4.2 (2.0)[†]
Peak abduction (°)	-2.8 (3.2)	-3.0 (3.2)	-2.7 (2.9)
Time to peak abduction (sec)	0.10 (0.07)	0.09 (0.06)	0.08 (0.05)
Z (+ = Internal/ - = External)			
Angle at initial contact (°)	4.5 (4.1)	4.5 (5.0)	4.5 (3.9)
Angle at toe off (°)	1.2 (3.9)	1.0 (3.9)	0.7 (3.6)*
Range of motion (°)	11.9 (4.5)	12.1 (4.3)	12.1 (4.3)
Peak internal rotation (°)	12.6 (5.1)	12.5 (5.1)	12.41(4.7)
Time to peak internal rotation (sec)	0.10 (0.03)	0.10 (0.03)	0.10 (0.03)

* Significantly different to motion control

[†] Significantly different to neutral

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Table 4. Comparison of hip joint kinematic parameters (mean (standard deviation)) in motion control, neutral and cushioned running shoes.

	Motion Control	Neutral	Cushioned
X (+ = Flexion/ - = Extension)			
Angle at initial contact (°)	25.2 (6.6)	25.9 (7.0)	25.3 (6.6)
Angle at toe off (°)	-7.2 (4.8)	-6.8 (5.2)	-7.6 (5.0)
Range of motion (°)	33.9 (6.4)	34.1 (6.6)	34.3 (6.5)
Peak flexion (°)	26.7 (6.1)	27.3 (6.5)	26.7 (6.1)
Time to peak flexion (sec)	0.24 (0.03)	0.23 (0.04)	0.23 (0.03)
Y (+ = Adduction/ - = Abduction)			
Angle at initial contact (°)	7.6 (4.5)	7.1 (4.8)	7.2 (4.5)
Angle at toe off (°)	4.3 (4.3)	4.1 (4.3)	3.8 (4.4)
Range of motion (°)	7.2 (3.7)	7.0 (3.4)	7.2 (3.9)
Peak adduction (°)	11.0 (4.5)	10.7 (4.7)	10.6 (4.8)
Time to peak adduction (sec)	0.07 (0.03)	0.07 (0.04)	0.08 (0.04)
Z (+ = Internal/ - = External)			
Angle at initial contact (°)	3.2 (4.9)	3.7 (5.0)	3.2 (4.8)
Angle at toe off (°)	-2.6 (4.8)	-2.6 (5.0)	-3.2 (5.0)
Range of motion (°)	7.7 (4.0)	8.0 (3.6)	8.1 (4.4)
Peak internal rotation (°)	4.2 (4.8)	04.5 (4.8)	4.1 (4.7)
Time to peak internal rotation (sec)	0.05 (0.08)	0.06 (0.08)	0.05 (0.07)

* Significantly different to motion control

† Significantly different to neutral

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Figure Legends

Figure 1 – Lateral view of a participant's lower leg and foot/shoe highlighting the rearfoot technical marker placement, an additional technical cluster is visible and located at the midshaft of the 5th metatarsal but was not utilised for this study

Figure 2 - Stance phase hip, knee and ankle joint kinematics in motion control (solid grey line), neutral (solid black line) and cushioned (dashed black line) running shoes, averaged across all participants (n = 28)

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Figure 1 – Lateral view of a participant's lower leg and foot/shoe highlighting the rearfoot technical marker placement, an additional technical cluster is visible and located at the midshaft of the 5th metatarsal but was not utilised for this study

29x34mm (300 x 300 DPI)

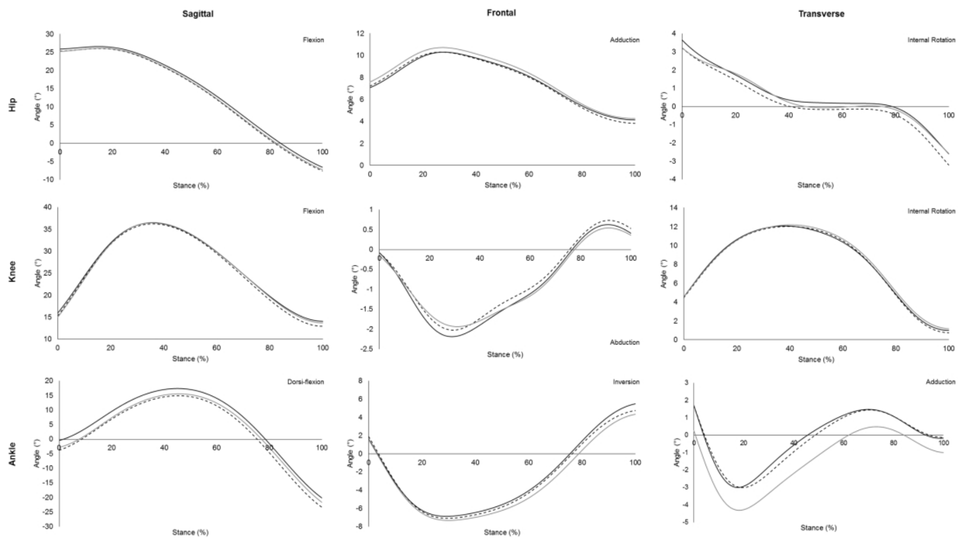

Figure 2 - Stance phase hip, knee and ankle joint kinematics in motion control (solid grey line), neutral (solid black line) and cushioned (dashed black line) running shoes, averaged across all participants (n = 28)

229x129mm (300 x 300 DPI)

Dear Editor and Reviews

Thank you for the valuable feedback provided on the manuscript [insert title]. We appreciate the time and effort you have put into your reviews and believe that you have raised a number of thought provoking and informative points that have helped us to enhance the quality of the submitted manuscript. Below is a point by point breakdown of the feedback received (bold font) and our responses. We have provided feedback in the following order; editor, reviewer 1 and reviewer 2.

We hope that the alterations made to the manuscript adequately address the points raised.

Best wishes

The authors

For Peer Review

Editor

JAB does not use structured abstracts. Please re-write the Abstract as a single paragraph using sentences rather than phrases following headings.

The abstract is presented as a single paragraph with no headings included.

In the Results section, please begin each paragraph with a topic sentence that presents the reader with a key result. The topic sentence should include the key result and any following text should provide substantiating information. Each topic sentence should correspond to a specific question asked or hypothesis posed. These are generally presented in the last paragraph of the Introduction. If you are presenting more key results than question/hypotheses posed then you will have to resolve the disparity.

Each paragraph begins with a topic sentence detailing which joint is of interest within that paragraph. Given the open first hypotheses, which states that lower limb kinematics will differ between motion control, neutral and cushioned running shoes, all of the paragraphs within the results section link specifically to this hypothesis. The second and third hypotheses relate to two specific variables (peak angle and range of motion) at the ankle joint in the frontal plane, both of which are covered within the opening paragraph of the results.

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All Figures and Tables should be cited parenthetically following a statement or a finding.

The opening sentences of the results section have been removed to better align the writing style with the requested format.

Please remove the text at the end of the Discussion related to future research.

Reference to future work within the discussion has been removed.

Reviewer: 1

L 31 – In the past classifications have been neutral/cushioned, stability, and motion control. Are you referring to cushioned shoes with higher stack heights like the Hoka

In this instance we are referring more generically to cushioned as a sub-classification of running shoes as opposed to specifically referring to a "maximalist" shoe such as the Hoka. We have found that the terminology around different sub-types of running shoes differs with neutral and cushioned or neutral and stability often appearing to be used interchangeably between different aspects of the literature. We have chosen to use the terms motion control, neutral and cushioned for consistency between this manuscript and an associated manuscript we have published on the influence of the same shoes upon inter-segmental foot kinematics. We have added an additional sentences (lines 31-35) to enhance the clarity here.

L95 – Could you provide a figure of this incision with the cluster? Did you perform any testing to test the properties of the heel counter after the 25 mm incision?

A figure has been added (figure 1). Two sentences (Lines 97-100) have also been added to this part of the method which highlight that as the work was part of a larger study 4 incisions were actually made within the shoe, but that this incision set was shown to have minimal impact upon the shoes structural integrity. An appropriate reference detailing the reference data for this suggestion has been added.

L102 – Was this anatomical reference done one time or repeated before each shoe condition?

The anatomical reference was undertaken once, in a barefoot condition. The wording of this sentence has been amended to better reflect this information (Line 104).

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L110 – Were any mechanical tests done to characterize the shoes? Cushioning, Foam Durometer, Flexibility? In our experience shoes labeled as stability can sometime have very similar properties to a neutral shoe if the foam specifications, geometries of the post etc. are not designed correctly or off their intended specification.

We appreciate this comment and understand how potential misplacement of key components within the motion control shoe may result in the shoe better matching a neutral shoe.

Unfortunately, we were not able to mechanically test the characteristics of the shoe. The information pooled from a range of online sources regarding the shoes detailed within table 1 is the only information we have on the shoes as this was deemed commercially sensitive by the manufacturer.

To acknowledge this point in some way we have added an additional caveat within the discussion to better highlight that differences reported and discrepancies between studies may be explained by differences in shoe design characteristics (Lines 208-210). We also acknowledge the lack of any mechanical testing on the shoes within the limitations now (Lines 228-231).

L148 – Could this be a result of the initial heel toe drop difference? In our experience the functional drop could also lead to this…in other words a softer foam when loaded will compress more leading to a different functional drop. Knowing the mechanical cushioning properties of the footwear used could provide some insight in this area.

As the reviewer highlights these differences, especially at the ankle in the sagittal plane, upon IC could be due to different heel toe drops between the footwear conditions. Additionally, a very valid point is raised about the potential for different functional drops due to the different midsole properties between the footwear conditions. To acknowledge the first of these points an additional section has been added to the discussion (lines21-216), which highlights change in ankle joint orientation upon IC and specifically links this to the different heel-toe drop between the shoes tested. However, as we have been unable to mechanically quantify the properties of the respective midsoles of the shoes we have not made explicit reference

For Peer Review

to potential functional drop differences between the footwear assessed within the study.

L191 – There is also great variability in the properties of the post foams uses in addition to the geometries between manufacturers and from season to season. In many styles the harder foam does not extend under the calcaneus much (for comfort reasons we believe) and as a result may have less impact on the movement of the heel. This may also explain some of the variability between studies and I believe cutting the shoe across the heel of a stability shoe and quantifying the location of the post of these studies should be something that is included.

The reviewer again makes a very good point here that the harder foam within the shoes midsole does not always extend fully under the calcaneus. As previously highlighted we did not have the capacity to mechanically test the shoes midsoles properties while undertaking the work and the manufacturer deemed the information commercially sensitive so did not provide these details. However, from manual palpation of the shoes tested within the study we believe that the harder density foam within the motion control running shoe does extend the full length of the calcaneus and for the majority of the midfoot as well on the medial aspect of the shoe. Previous studies have not provided explicit details about the midsole properties and geometries of the motion control and neutral shoes assessed, so our study is at least consistent with these. However, we do acknowledge the importance of this information if available for future work. We have included the caveat within the discussion that a lack of consistent in shoe design features may explain some of the disparity between studies (Lines 208-210).

Table 2 - There is some formatting differences in the cushioned column

The formatting of this column has been revised to ensure consistency across all tables and columns.

For Peer Review

Reviewer: 2

As pointed out in the limitations paragraph, it is very important to acknowledge (early on in the manuscript) that kinematics are analyzed for running in 3 specific shoe models. These models are considered to be neutral, motion control or cushioned by the manufacturer, but no objective measures are presented that allow the reader to place these specific models within the existing literature on these shoe types. This is probably mainly a weakness of the field as long as no such objective measures are developed. In any case this is an important limitation that should be communicated early on in the manuscript.

We thank the reviewers for flagging this important point and for providing us with the confidence to make a statement such as this within the introduction. We have now added a statement which highlights that no objective method for the classification of running shoes into motion control, neutral and cushioned categories exists and as such the shoes are typically categorised based upon manufacturers recommendations (Lines 30-32).

The authors point out that some studies have placed markers on the shoe rather than on the foot, and that discrepancies between the motion of the foot and the shoe have been reported (also see https://www.sciencedirect.com/science/article/pii/S0966636218304405). Still in the current study the second and fifth metatarsal head markers appear to be placed on the shoe, not on the foot. This should be acknowledged.

Apologies, we did not highlight at this instance in the manuscript that the static trial was recorded in a barefoot condition. Recording the static trial in the barefoot condition enabled the anatomical markers at the identified landmarks to be placed directly on the foot. This detail has now been added to the end of the relevant sentence within the method to enhance the clarity (line 104). Additionally, we should have identified the first rather than second metatarsal head, this was a typo.

For Peer Review

Thank you for highlighting the recent paper by Alcantara, Trudeau and Rohr this has now also been cited within our manuscript.

L72: Cheung and Ng should be reference 9

Thank you for flagging this error, it has now been corrected (now reference 11).

Information on footstrike patterns of all 28 participants would be useful. Were all participants rearfoot strikers, was data of rear-, mid and forefoot strikers pooled?

A mixture of foot strike patterns were used within the study and the data pooled. While this provides a less homogenous sample we believe that this approach increases the generalisability of the findings. Exploration of the data on an individual level suggests that foot strike pattern was consistent across each footwear conditions. As such we are confident that the findings presented are not influenced by changes in foot strike patterns between footwear conditions.

We have now provided a sentence within the method (lines 76-78) which highlights the recruitment of participants with a range of foot strike patterns.

For Peer Review

The foot was treated as a single rigid segment. It appears that data is available to consider the foot as multi-segments (ref 36). Why was it simplified as a rigid segment in the current study and how could that have influenced the results? Please elaborate.

Rationale for presenting the foot as a single rigid segment within this study was twofold. Firstly, previous studies within this area (Cheung and Ng, 2007; Lilley et al., 2012) had utilised only a single segment foot model and we believe taking this approach increases the comparability of the findings. Secondly, and more pragmatically, the assessment of both lower limb and multi-segmental foot kinematics was too large for a single publication.

In relation to how this decision may have influenced the findings we believe that changes in midfoot or forefoot motion patterns would largely be neglected in the findings of the current study as the technical marker cluster for the single segment foot was located on the rearfoot. As such the findings reported here correspond to primarily alterations in rearfoot (calcaneus) motion between the 3 footwear conditions.

L209-211: since the increase in peak internal knee rotation was non-significant, this is rather speculative. Was there a correlation between peak foot eversion/abduction and internal knee rotation?

Thank you for raising this very valid point. Having gone back to the data no correlations between peak foot eversion/abduction and internal knee rotation were evident. As such we accept the reviewers view point that the suggestions were overly speculative and as such we have removed this information from the manuscript. Instead we have discussed the transverse plane ankle joint kinematic findings (lines 216-224) and added additional information in to the second paragraph of the discussion to acknowledge the changes at the knee (lines 179-183).

L242-244: Another possible explanation for differences with and within the literature is that each brand (and study) seems to have their own specific shoe model and label it "motion control" or "cushioned".

The reviewers again make a very good point here and we have tried to make this point more explicit throughout the manuscript by acknowledging the lack of an objective method to sub-classify running shoes within the introduction (lines 30-32) and also within the discussion (lines 208-210)

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