



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

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

2 **Kinematics**

3

4 **Abstract**

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

20 **Key Words:** footwear, hip, knee, ankle

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22 **Word Count:** 2,934 words

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Introduction

24 Traditional running-injury paradigms have been challenged within the literature¹, yet
25 still underpin running shoe design. As such, running shoes are still designed with stability and
26 cushioning features which are thought to influence the rate and/or magnitude of foot motion
27 and impact loading^{2,3}. Running shoes are often categorised based upon their design features
28 and may broadly be classified as trail, performance, minimalist or conventional running shoes⁴
29 ⁶. Conventional running shoes are often further sub-classified based upon their specific stability
30 and cushioning features, in to motion control, neutral and cushioned categories⁴⁻⁶. Currently no
31 objective method for this sub-classification exists and as such running shoes are often classified
32 based upon manufacturer recommendations. Furthermore, these terms are by no means uniform
33 with different manufactures, retailers or publications often using neutral/stability or
34 cushioned/neutral interchangeably⁴⁻⁸. For clarity the terms motion control, neutral and
35 cushioned will be used exclusively throughout this manuscript. Motion control running shoes
36 aim to reduce the magnitude and/or rate of pronation with a view to enhancing the propulsive
37 efficiency of the foot, in comparison to neutral and cushioned shoes^{6,9,10}. In contrast, cushioned
38 running shoes aim to reduce the magnitude and/or rate of impact loading, and increase foot
39 motion relative to neutral and motion control running shoes^{6,9,10}. Neutral running shoes
40 combine a number of motion control and cushioning features with a view to providing some
41 additional stability compared to cushioned running shoes, and greater force attenuation than
42 motion control running shoes^{6,9,10}.

43 Studies^{11,12} have demonstrated that motion control running shoes reduce rearfoot
44 eversion compared to neutral shoes. However, as is common within footwear biomechanics,
45 these studies^{11,12} placed markers on the shoe. Discrepancies between the motion of the foot and
46 the shoe have been reported¹³⁻¹⁵ and as such, the findings of studies using shoe based markers

47 should be interpreted with caution. The only study¹⁰ known to the authors comparing in-shoe
48 foot motion, when running in motion control and cushioned running shoes, found no significant
49 differences in rearfoot eversion. Further work is required to explore the influence of motion
50 control, neutral and cushioned running shoes on in-shoe foot motion.

51 Assessment of rearfoot eversion has been widely reported over the past 40 years^{11,12,17-19}
52 as a measure of how footwear influences foot motion. This approach offers limited
53 understanding of the influence footwear modifications may have upon the sagittal and
54 transverse plane motions of the foot, or upon more proximal joints. The assessment of how
55 footwear influences lower limb kinematics may help to elucidate mechanisms by which injury
56 risk can be mitigated; as hip and knee joint kinematics have been linked to the development of
57 overuse running injuries²⁰⁻²³. Two studies^{10,24} have demonstrated that motion control running
58 shoes reduce internal tibial rotation compared to cushioned or neutral running shoes,
59 respectively. While Hutchison et al²⁵ reported significant reductions in internal knee rotation
60 when running in motion control shoes compared to neutral shoes. These findings highlight that
61 motion control, neutral and cushioned running shoes have the potential to influence more
62 proximal joint kinematics. However, there is a lack of published data relating to the influence
63 of these types of commercially available running shoes upon three dimensional (3D) lower
64 limb kinematics. The aim of this study was to determine the influence of motion control, neutral
65 and cushioned running shoes on lower limb kinematics. Three hypotheses were tested; (1)
66 lower limb kinematics will differ between motion control, neutral and cushioned running shoes,
67 (2) motion control running shoes will reduce the magnitude of ankle joint eversion compared
68 to neutral and cushioned running shoes, and (3) cushioned running shoes will increase the
69 magnitude of ankle joint eversion compared to neutral and motion control running shoes.

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Methods

72 Based upon an *a priori* sample size calculation, using the method of Eng²⁶ and the data
73 of Cheung and Ng¹¹, 28 active males (26 ± 7 years, 1.77 ± 0.05 m, 79 ± 9 kg) were recruited
74 for this study. Participants were free from injury and/or illness at the time of testing, as
75 determined by a health screening questionnaire. On average participants reported exercising
76 three to four times per week, including running two to three times per week. Foot strike pattern
77 was not controlled within the study to enhance the generalisability of the findings; 19
78 participants were rearfoot, 6 midfoot and 3 forefoot strikers. Ethical approval was granted for
79 this study by the Research Ethics Committee of the host institution and written informed
80 consent was provided by all participants prior to testing.

81 Participants attended one test session lasting between 1 – 1.5 hours. At the beginning
82 of the session, participants undertook a 10 minute familiarization period on a Jaeger LE 300 C
83 treadmill (Erich Jaeger GmbH & Co, Wuerzburg, Germany), to minimise kinematic
84 differences between overground and treadmill conditions^{27,28}. After the familiarization period,
85 anatomical and tracking markers were attached in line with a four segment lower limb model
86 (described below). An eight camera VICON MX motion analysis system (VICON Motion
87 Systems Ltd., Oxford, England), operating at 200Hz, was used to track the position of retro-
88 reflective markers attached to foot and lower limb. Prior to data collection, the VICON system
89 was calibrated following the manufacturer's guidelines.

90 To define the foot, shank, thigh and pelvis, 14mm retro-reflective markers were
91 attached to the right limb at the following locations; first and fifth metatarsal heads, medial and
92 lateral malleoli, medial and lateral femoral epicondyles, and bilaterally to the anterior and
93 posterior superior iliac spines. In accordance with the calibrated anatomical system technique²⁹,
94 marker clusters were used to track each segment during dynamic trials. The foot was tracked

95 by a triad marker cluster attached to the posterior-lateral aspect of the calcaneus at the height
96 of the Achilles tendon attachment (Figure 1). To enable the marker cluster to be attached
97 directly to the foot, a 25 mm incision was made within each shoe^{30,31}. Four incisions were made
98 within the shoe in total, as this study was part of a larger project which also explored inter-
99 segmental foot kinematics. The incision set was found to have minimal influence upon the
100 running shoes structural integrity³¹. The thigh and shank were tracked by rigid clusters,
101 consisting of four non-collinear markers, located on the distal-lateral aspect of the segment.
102 The pelvis was tracked by a rigid cluster of four non-collinear markers attached to the proximal-
103 posterior aspect of the segment. Once participants were fully fitted with both anatomical and
104 tracking markers a single, static trial was recorded, in a barefoot condition. This enabled the
105 relevant anatomical reference frames to be calculated for each segment. After the static trial
106 was recorded anatomical markers were removed.

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

114 Raw marker trajectories were reconstructed, labelled and filtered using a 10Hz
115 Butterworth filter, within VICON Nexus 1.7.1 (Vicon Motion Systems Ltd., Oxford, England).
116 Gaps, of up to five frames, in marker trajectories were filled using the in-built pattern fill
117 function within VICON Nexus 1.7.1. Processed trials were cropped to five consecutive gait
118 cycles and exported to Visual 3D (C Motion Inc., Leicester, England) where 3D hip, knee and

119 ankle joint kinematics were calculated. Gait cycle parameters were identified from the
120 kinematic data³². Joint angles were averaged and time normalised to 100 % stance phase
121 duration. All joint angles were normalised for each participant to their static posture recorded
122 barefoot in a relaxed standing position, enabling differences in absolute joint angles to be
123 compared between footwear conditions³³. Discrete angles were pre-selected, in line with the
124 literature³⁴, to describe the motion pattern of each joint and extracted for statistical analysis.
125 The discrete variables used to describe stance phase kinematics were angles at initial contact
126 (IC) and toe off (TO), joint range of motion (ROM), peak angles and time to peak angle.

127 Descriptive statistics (mean (standard deviation)) were calculated within Microsoft
128 Excel 2013 (Microsoft, Redmond, WA, USA). Statistical analysis was undertaken in SPSS 20
129 (IBM, Armonk, NY, USA). Prior to data analysis, all data were explored for normal distribution
130 using a Shapiro-Wilk test. Where data met parametric assumptions, differences between shod
131 conditions were explored using a one-way repeated measures analysis of variance (ANOVA).
132 Where significant main effects were observed, post hoc pairwise comparisons were undertaken.
133 Where data violated parametric assumptions, differences between shod conditions were
134 explored using Friedman's ANOVA. Where significant main effects were observed, pairwise
135 comparisons were conducted post hoc. Partial eta squared (η^2) was used as an estimate of effect
136 size for the repeated measures ANOVA and Kendall's W (W) was used for Friedman's
137 ANOVA. Effect sizes were interpreted as follows; small effect $\geq .10$, moderate $\geq .30$ and large
138 $\geq .50$ ³⁵. The level of significance for main effect within the study was set at $p < .05$, with post
139 hoc comparisons Bonferroni corrected.

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Results

142 Significant main effects were observed for ankle joint dorsi-flexion upon IC ($p = .01$,
143 $W = .16$) and peak ankle dorsi-flexion in stance ($p = .02$, $W = .14$) (Table 2, Figure 2). The
144 ankle was significantly more dorsi-flexed upon IC by 2.4° and 3.3° when running in the neutral
145 shoe compared to the motion control ($p = .02$) and cushioned shoes ($p = .03$), respectively.
146 Peak ankle joint dorsi-flexion was significantly increased by 2.6° when running in the neutral
147 shoe compared to the cushioned shoe ($p = .02$). In the frontal plane, significant main effects
148 were observed for ankle joint inversion at TO ($p = .05$, $\eta^2 = .11$) and peak ankle joint eversion
149 ($p = .04$, $W = .12$). The ankle was significantly more inverted at TO by 1° when running in the
150 neutral shoe compared to the motion control shoe ($p = .04$), and peak ankle joint eversion was
151 significantly greater by 0.2° in the motion control shoe compared to the cushioned shoe ($p =$
152 $.05$). Significant main effects were reported for ankle joint adduction upon IC ($p = .03$, $\eta^2 =$
153 $.12$) and peak ankle joint abduction ($p = .01$, $\eta^2 = .15$). The ankle joint was significantly ($p =$
154 $.03$) more adducted upon IC when running in the neutral shoe compared to the motion control
155 shoe by 1.4° . Peak ankle joint abduction was significantly ($p = .02$) greater when running in
156 the motion control shoe compared to the neutral shoe by 1.4° .

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

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

167

168 Discussion

169 This study examined the impact of motion control, neutral and cushioned running shoes
170 on 3D lower limb kinematics. The findings of this study support hypotheses one with
171 significant differences reported in both knee and ankle joint movement patterns between
172 footwear conditions (Tables 2 & 3). However, these significant differences are small in terms
173 of both magnitude ($\leq 3.3^\circ$) and effect size ($\leq .17$), and are below the reported minimal
174 detectable difference ($3-6^\circ$) for lower limb kinematics during running³⁶. As such the significant
175 changes must be interpreted with caution.

176 The assessment of hip, knee and ankle joint motion within this study provides a more
177 comprehensive insight into how different types of footwear influence lower limb kinematics,
178 in comparison to single joint assessments typically reported within the literature^{11,24,25}.
179 Statistically significant differences in knee and ankle joint movement patterns, that would be
180 missed by traditional assessments of ankle joint eversion alone, were identified within this
181 study. Furthermore, changes in knee joint kinematics, across all three planes, were reported
182 which further highlight the efficacy of different types of conventional running shoes to
183 influence motion patterns higher up the kinematic chain. The magnitude of change between
184 footwear conditions reduced more proximally within the kinematic chain. A finding that is
185 supported by Lilley et al¹². Additional work undertaken by the authors of this study further
186 supports the suggestion that the influence of running shoes upon joint kinematics reduces as
187 you move proximally up the kinematic chain, with changes of a larger magnitude reported for

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

193 Peak ankle eversion was greater when running in the motion control shoe compared to
194 the cushioned shoe, however both the magnitude of change (0.2°) and the effect size ($W = .12$)
195 were small (Table 2). This finding contrasts with what would be expected from the design aims
196 of each shoe and the previous literature^{11,12}, and rejects hypotheses two and three. Studies^{11,12}
197 using shoe-based markers have reported significant reductions in peak RF eversion of between
198 0.9° and 6.5° when running in motion control shoes compared to neutral shoes. In contrast,
199 Butler et al¹⁰ reported no significant differences in in-shoe foot motion between motion control
200 and cushioned running shoes, suggesting small differences between conditions, however no
201 data was reported by the authors. The disparity between the studies using shoe based
202 markers^{11,12} and those tracking in-shoe foot motion, such as this one, is important. The existing
203 literature suggests that peak shoe eversion is lower in motion control shoes compared to neutral
204 shoes, potentially due to the more rigid heel counter. However, the reduction in peak shoe
205 eversion does not appear to be replicated by the motion of the foot within the shoe. This is
206 supported by Van Gheluwe, et al³⁹ who reported larger discrepancies between in-shoe foot
207 motion and the motion of the shoe with more rigid heel counters, such as those built in to the
208 motion control shoe. It should be noted at this time that the lack of consistency in running shoe
209 classification and design features across studies and manufacturers may also explain some of
210 the disparity between studies.

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

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

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

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247

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340

341 **Tables and Legends**

342

343 Table 1. Design characteristics of the motion control, neutral and cushioned shoes used within
 344 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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346

347 Table 2. Comparison of ankle joint kinematic parameters (mean (SD)) in motion control,
 348 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)

349 * Significantly different to motion control

350 † Significantly different to neutral

351 Table 3. Comparison of knee joint kinematic parameters (mean (SD)) in motion control, neutral
 352 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)

353 * Significantly different to motion control

354 [†] Significantly different to neutral

355 Table 4. Comparison of hip joint kinematic parameters (mean (standard deviation)) in motion
 356 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)

357 * Significantly different to motion control

358 † Significantly different to neutral

359 **Figure Legends**

360

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

364

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

368



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)

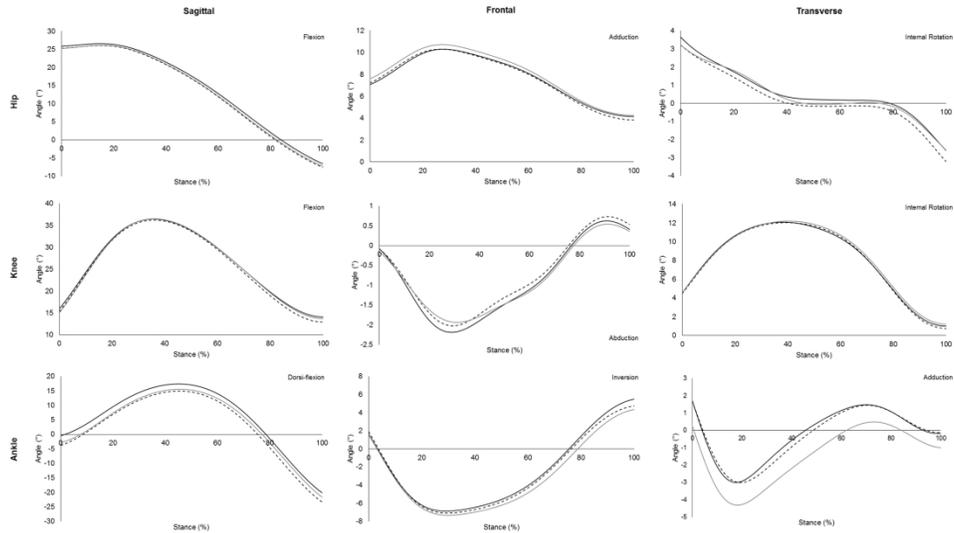


Figure 2 - Stance phase hip, knee and ankle joint kinematics in motion control (solid grey line), neutral (solid black line) and cushioned (dashed black line) running shoes, averaged across all participants (n = 28)

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.

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).

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 (lines 211-216), 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

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.

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.

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.

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)