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1 **3-D kinematic comparison of treadmill and overground running.**

2  
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26 analysis.

27

## 28 **ABSTRACT**

29 Studies investigating the mechanics of human movement are often conducted using  
30 the treadmill. The treadmill is an attractive device for the analysis of human  
31 locomotion. Studies comparing overground and treadmill running have analyzed  
32 discrete variables, however differences in excursion from footstrike to peak angle  
33 and range of motion during stance have yet to be examined. This study aimed to  
34 examine the 3-D kinematics of the lower extremities during overground and treadmill  
35 locomotion to determine the extent to which the two modalities differ. Twelve  
36 participants ran at 4.0m/s in both treadmill and overground conditions. 3-D angular  
37 kinematic parameters during the stance phase were collected using an eight camera  
38 motion analysis system. Hip, knee and ankle joint kinematics were quantified in the  
39 sagittal, coronal and transverse planes, then compared using paired t-tests. Of the  
40 parameters analyzed hip flexion at footstrike 12° hip range of motion 17°, peak hip  
41 flexion 12.7°, hip transverse plane range of motion 8° peak knee flexion 5° and peak  
42 ankle excursion range 6.6°, coronal plane ankle angle at toe-off 6.5° and peak ankle  
43 eversion 6.3° were found to be significantly different. These results lead to the  
44 conclusion that the mechanics of treadmill locomotion cannot be generalized to  
45 overground.

## 46 **INTRODUCTION**

47 A number of studies investigating the mechanics of human movement have been  
48 conducted using the treadmill. The treadmill presents an environment where

49 variables such as velocity and gradient can be standardized and reproduced  
50 consistently (Schache et al., 2001). Furthermore, the treadmill allows a larger  
51 number of steps to be captured and ensures that continuous movement kinematics  
52 are obtained. Thus the treadmill may facilitate a more repeatable pattern of  
53 movement in comparison to the short discontinuous trials associated with  
54 overground analyses (Fellin et al., 2010). Although this is advantageous it must be  
55 demonstrated that the treadmill does not alter the mechanics of the examined  
56 movements in comparison to overground motion (Brand and Crowninshield, 1984).  
57 There remains debate regarding the assumption that treadmill running approximates  
58 overground running. A number of investigations have been conducted examining the  
59 biomechanical differences between the two conditions (Nigg et al., 1995, Schache et  
60 al., 2001, Fellin et al., 2010, Riley et al 2008 Frishberg, (1983), and Gamble et al.,  
61 (1988); the results however are often conflicting.

62

63 Using a theoretical literature review Van Ingen Schenau, (1980) proposed that the  
64 mechanics of overground and treadmill locomotion are similar provided that velocity  
65 is maintained. A number of studies have examined the kinematic differences  
66 between overground and treadmill walking. Lee and Hidler, (2007) established that  
67 peak flexion and extension measures of the lower extremities did not differ between  
68 the two conditions. Alton et al., (1998), Matsas et al., (2000) and Riley PO et al.,  
69 (2007) found comparable sagittal plane knee kinematics during overground and  
70 treadmill locomotion. Strathy et al., (1983) found that knee joint angular kinematics in  
71 the coronal and transverse planes did not differ significantly between the two  
72 conditions. Alton et al., (1998) and Riley PO et al., (2007) reported significantly  
73 greater hip range of motion and flexion angles during treadmill locomotion.

74

75 The kinematics of running have also been compared between overground and  
76 treadmill locomotion. Frishberg, (1983), Gamble et al., (1988) and Schache et al.,  
77 (2001) observed that overground running was associated with increased hip flexion  
78 at initial contact, whilst Schache et al., (2001) found no alterations in transverse  
79 plane hip motion between the two conditions. There is currently a paucity of  
80 comprehensive comparisons regarding the 3-D kinematics of the lower extremities  
81 during treadmill and overground running during the stance phase. Riley PO et al.,  
82 (2008) examined the differences in hip, knee and ankle joint kinematics from both  
83 treadmill and overground motion. However they examined only maximum and  
84 minimum angles of the full gait cycle, therefore as the majority of these occurred  
85 during the swing phase; angles during the stance phase were not compared.  
86 Similarly Fellin et al., (2010) investigated lower extremity motion during both treadmill  
87 and overground locomotion; their examination utilized a trend symmetry design  
88 which is an effective method of comparing the similarities between kinematic curves,  
89 but it does not examine the differences in lower extremity angulation between the  
90 two conditions. Furthermore, investigations that have been conducted to date, have  
91 been restricted to discrete kinematic parameters and have thus failed to consider the  
92 range of motion and excursion from footstrike to peak angle during stance.

93

94 The aim of the current investigation was to assess the extent to which the stance  
95 phase mechanics of overground and treadmill locomotion are similar during running.  
96 Specifically the 3-D angular kinematics of the lower extremity joints were observed  
97 during overground running and compared to the corresponding data from the  
98 treadmill.

## 100 **METHOD**

### 101 *Participants*

102 Eleven males and one female who were free from musculoskeletal injury volunteered  
103 to take part in this study. Participants were active recreational runners engaging in  
104 training at least 3 times per week whilst completing a minimum of 25 km per week  
105 and had previous experience of treadmill running. Participants encompassed a range  
106 of footstrike characteristics. The mean characteristics of the participants were; age  
107  $22.5 \pm 4.2$  years, height  $1.71 \pm 0.06$ m and body mass  $75.4 \pm 8.4$  kg. An a priori  
108 power analysis was conducted using the Hopkins method based on a moderate  
109 effect size and a power measure of 80%, which suggested that 12 subjects were  
110 adequate for the design. The study was approved by the School of Psychology  
111 ethical committee, and all participants provided written informed consent.

### 112 *Procedure*

113 All kinematic data were captured at 250 Hz via an eight camera motion analysis  
114 system (Qualisys Medical, Goteburg, Sweden). Two separate camera systems were  
115 used to collect each mode of running. Calibration of the Qualysis<sup>TM</sup> systems was  
116 performed before each data collection session. Only calibrations which produced  
117 average residuals of less than 0.85 mm for each camera for a 750.5 mm wand  
118 length and points above 4000 in all cameras were accepted prior to data collection.  
119 The order in which participants performed in each condition was counterbalanced.  
120 The marker set used for the study was based on the calibrated anatomical systems  
121 technique (CAST) technique using a 6 degrees of freedom (DOF) model (Cappozzo  
122 et al., 1995). A static trial was conducted with the participant in the anatomical

123 position (Figure 1) allowing the positions of the anatomical markers to be referenced  
124 in relation to the tracking clusters, following which they were removed. Markers used  
125 for tracking remained in place for the duration of the treadmill and overground  
126 analyses.

127

128 Retro-reflective markers were attached to the 1st and 5th metatarsal heads, medial  
129 and lateral malleoli, medial and lateral epicondyle of the femur, greater trochanter of  
130 the right leg, iliac crest, anterior superior iliac spines and posterior superior iliac  
131 spines with tracking clusters positioned on the shank and thigh. All markers were  
132 positioned by the first author. Hip joint centre was determined based on the Bell, et  
133 al., (1989) equations via on the positions of the PSIS and ASIS markers. Each rigid  
134 cluster comprised four 19mm spherical reflective markers mounted to a thin sheath  
135 of lightweight carbon fiber with length to width ratios of 2.05:1 and 1.5:1 for the femur  
136 and tibia respectively, in accordance with Cappozzo et al., (1997) recommendations.  
137 Participants wore the same footwear throughout Saucony pro grid guide 2 in sizes 6-  
138 9.

139

140 **@@@Figure 1 near here@@@**

141

142 Given that the treadmill did not feature an integrated force platform, heel strike and  
143 toe-off events during both treadmill and overground running were determined using  
144 kinematic data based on the Dingwell et al., (2001) method. Footstrike was deemed  
145 to be the first occurrence of peak knee extension and toe-off was determined as the  
146 second occurrence of the peak knee extension (Sinclair et al., 2012).

147

148 *Overground*

149 In the overground condition participants ran at 4.0 m/s in one direction across a 22 m  
150 long biomechanics laboratory floor (Altrosports 6 mm, Altro Ltd, Letchworth Garden  
151 City, Hertfordshire). Running velocity was monitored using infrared timing gates  
152 Newtest 300 (Newtest, Oulu Finland); a maximum deviation of  $\pm 5\%$  from the set  
153 velocity was allowed. Runners completed a minimum of six successful trials. A  
154 successful trial was defined as one within the specified velocity range, where all  
155 tracking clusters were in view of the cameras and with no evidence of gait  
156 modification due to the experimental conditions.

157

158 *Treadmill*

159 A Woodway<sup>TM</sup> (ELG, Steinackerstrasse D-79576 Weil Rhein-Germany) high power  
160 slatted treadmill maintained at a gradient of 0% was used throughout. Participants  
161 were given a five minute habituation period, in which participants ran at the  
162 determined velocity, following which the treadmill was stopped for 30's, and  
163 participants dismounted the treadmill before mounting the treadmill for data analysis  
164 in accordance with the Alton et al., (1998) recommendation. When participants  
165 indicated that they were ready to begin, the treadmill was started and the velocity of  
166 the belt was gradually increased until the speed matched that of overground  
167 locomotion (4.0m/s). Six trials were recorded.

168

169 *Data Processing*

170 Trials were processed in Qualisys Track Manager in order to identify anatomical and  
171 tracking markers then exported as C3D files. Kinematic parameters were quantified  
172 using Visual 3-D (C-Motion, Gaithersburg, USA) after marker data was filtered using



173 a low pass Butterworth 4<sup>th</sup> order zero-lag filter at a cut off frequency of 10 Hz which  
174 was selected as being the frequency at which 95% of the signal power was below. 3-  
175 D kinematics of the hip, knee and ankle joints were calculated using an XYZ cardan  
176 sequence of rotations (where X is flexion-extension; Y is ab-adduction and is Z is  
177 internal-external rotation). All data were normalized to 100% of the stance phase  
178 then processed gait trials were averaged. 3-D kinematic measures from the hip,  
179 knee and ankle which were extracted for statistical analysis were 1) angle at  
180 footstrike, 2) angle at toe-off, 3) range of motion from footstrike to toe-off during  
181 stance, 4) peak angle during stance and 5) peak angular excursion from footstrike to  
182 peak angle. These variables were extracted from each of the six trials for each joint  
183 in all three planes of rotation and the data was then averaged across participants for  
184 statistical analysis. Participants kinematic curves for each joint angle were time  
185 normalized to stance were ensemble averaged for visual purposes only.

186

### 187 *Statistical analysis*

188 Descriptive statistics (mean  $\pm$  standard deviation) were calculated for the outcome  
189 measures. To compare differences in 3-D kinematic parameters paired t-tests were  
190 utilized with an adjusted alpha level of  $p=0.01$  based on the number of comparisons  
191 made for each joint in each of the three planes of rotation. The Shapiro-Wilk statistic  
192 for each condition confirmed that the data were normally distributed. All statistical  
193 procedures were conducted using SPSS 17.0 (SPSS Inc, Chicago, USA).

## 194 **RESULTS**

195 Figure 2 presents mean 3-D angular motions of the hip, knee and ankle during the  
196 stance phase of both treadmill and overground running. Tables' 1, 2 and 3 show  
197 means, standard deviations and the results of the statistical analysis of the outcome  
198 measures.

199

200 Of the 45 observed parameters 8 exhibited significant  $p \leq 0.01$  differences between  
201 overground and treadmill running (tables 1-3). The majority of the kinematic  
202 differences between the two modalities were observed in the sagittal plane. At the  
203 hip joint overground runners exhibited  $12^\circ$ ,  $p=0.001$  more hip flexion at footstrike,  
204  $17^\circ$ ,  $p=0.001$  more hip range of motion and  $12.7^\circ$ ,  $p=0.001$  more peak flexion than in  
205 the treadmill condition and  $8^\circ$ ,  $p=0.01$  more transverse plane range of motion. At the  
206 knee overground runners were found to be associated with greater peak knee flexion  
207  $5^\circ$ ,  $p=0.01$ . At the ankle overground runners exhibited  $6.5^\circ$ ,  $p=0.01$  more excursion  
208 from footstrike to peak angle and  $5.7^\circ$ ,  $p=0.007$  more inversion, whereas treadmill  
209 runners were associated with  $6.3^\circ$ ,  $p=0.006$  more peak eversion.

210

211 **@@@@@ Figure 2 near here @@@@@**

212

213 **@@@@@ Table 1 near here @@@@@**

214 **@@@@@ Table 2 near here @@@@@**

215 **@@@@@ Table 3 near here @@@@@**

216 **DISCUSSION**

217 The aim of this study was to provide a 3-D kinematic comparison of treadmill and  
218 overground running. This study represents the first comparative study specifically  
219 concerning the lower extremity 3-D angular range of motion and peak excursion  
220 parameters during the stance phase between the two conditions. The results indicate  
221 that several kinematic differences were observed between the two running modalities.

222

223 It has been proposed that the mechanics of treadmill locomotion are similar to  
224 overground provided that velocity remains constant (Van Ingen Schenau, 1980).  
225 However, in this study significant differences between overground and treadmill  
226 running were found for sagittal plane hip rotation. Overground running was associated  
227 with increased peak hip flexion and flexion angle at initial contact. This concurs with  
228 the findings of Schache et al., (2001) who observed similar increases in hip flexion  
229 during overground running.

230

231 Overground running in this experiment was also associated with an increased range of  
232 motion in hip flexion-extension, which was a product of increased hip flexion at  
233 footstrike during overground running, as hip flexion at toe-off was found to be similar  
234 for the two conditions. This finding agrees with the findings of Frishberg (1983),  
235 Gamble et al., (1988) and Schache et al., (2001). These findings may be attributable to  
236 the reduced stride lengths that have been observed previously during treadmill running  
237 (Wank et al., 1998). Furthermore, it is hypothesized that the slatted treadmill belt may  
238 have acted as a visual cue which served to further accentuate this adaptation causing  
239 the large difference between the two conditions. Future, research may therefore wish

240 to investigate the influence of both slatted and smooth treadmill belts of the 3-D  
241 kinematics of running.

242

243 Furthermore, Alton et al., (1998) hypothesized that participants utilized these  
244 mechanics as a means of avoiding falling off the back of the treadmill and/or keeping  
245 up with the belt speed. The results of the current investigation appear to oppose this  
246 notion in that participants did not exhibit similar patterns, despite moving at a greater  
247 velocity, as fear of falling and pressure to maintain a stipulated speed would  
248 theoretically be amplified by an increased belt velocity. It is also probable that the  
249 length of the treadmill utilized during this investigation (1.0m longer than that reported  
250 by Alton et al., 1998), decreased participants concern that they might fall off the  
251 treadmill. Future investigations may wish to assess subjective feedback from  
252 participants in order to determine the underlying mechanisms behind gait alterations.

253

254 The significant increase in transverse plane range of motion contradict the results of  
255 Schache et al., (2001) and Fellin et al., (2010) who found no differences in transverse  
256 plane hip joint angular kinematics between overground and treadmill locomotion.  
257 Furthermore, the transverse plane hip rotation curve appears to contrast previous  
258 research investigating running kinematics, in that participants exhibited external  
259 rotation at footstrike and continued externally rotating throughout stance. It is  
260 hypothesized that this is attributable to the predominantly male sample utilized in the  
261 current investigation, as males have been shown to exhibit greater active hip external  
262 rotation than females (Ferber et al., 2003).

263

264 The increase in peak knee flexion during overground running has not been reported  
265 previously. It is proposed that this finding is attributable to the difference in centre of  
266 mass progression during overground running as the centre of mass moves over the  
267 stance limb the proximal end of the tibia must move forwards, facilitating an increase in  
268 knee flexion. Similarly, the significant increase in the angular excursion from footstrike  
269 to peak dorsiflexion has not been reported previously within the literature. It is  
270 proposed that this is also attributable to the increase in centre of mass progression in  
271 the overground condition. Given that the foot is fixed during the majority of the stance  
272 phase, forward motion of the centre of mass forces the tibia to move over the ankle  
273 joint creating the dorsiflexion range of motion. This finding may also relate to  
274 differences in surface hardness between the two conditions. The increase in  
275 dorsiflexion range of motion in conjunction with peak knee flexion may act as a  
276 deceleration mechanism which serves to reduce loading of the lower extremity  
277 structures (Bobbert et al., 1992).

278

279 Observation of the statistical data and kinematic curves of the knee joint in the  
280 coronal plane suggests that the knee is biased towards abduction for the entire  
281 stance phase. This is perhaps surprising given the predominantly male sample  
282 (Malinzak et al., 2001), yet this finding does concur with the findings of Ferber et al.,  
283 (2003) who also observed that male runners were biased towards abduction. Given  
284 that knee angular kinematics outside the sagittal plane are sensitive to the method  
285 used to predict the hip joint centre (Stagni et al., 2000); it is possible that inter-study  
286 variations in knee coronal plane mechanics may relate to the different methods of

287 quantifying the location of the hip joint centre. A number of techniques currently exist  
288 which may include radiographic (Bell et al., (1990), anatomical Bell et al., (1989),  
289 functional (Cappozzo, 1984; Leardini et al., 1999) and projection (Weinhandl and  
290 O'Connor, 2010) based methods, all of which may influence the resultant knee  
291 position (Stagni et al., 2000). Although the efficacy and validity of each method have  
292 been reported to justify their utilization, there is currently a lack of consensus  
293 regarding the most appropriate technique which future research may wish to  
294 address.

295

296 During during treadmill running, the ankle was found to be slightly more dorsiflexed at  
297 footstrike. This finding contrasts the findings of Wank et al., (1998), Fellin et al., (2010)  
298 and Nigg et al., (1995), who found decreased ankle dorsiflexion at footstrike. This  
299 change in sagittal plane ankle position at foot contact may relate to a change in strike  
300 pattern as plantar/dorsi flexion of the ankle is one of the mechanisms by which leg  
301 stiffness is regulated (Bishop et al., 2006). It is hypothesized that the reduced stiffness  
302 of the treadmill surface may have led to the increased dorsiflexion at footstrike as  
303 runners have been found to adjust their leg stiffness in response to differences in  
304 surface hardness (Bishop et al., 2006).

305

306 The significant increase in eversion magnitude is in contrast to the observations of  
307 Fellin et al (2010) who reported no differences in rearfoot eversion parameters  
308 between treadmill and overground running. This finding may relate to the deformation  
309 characteristics of the surface during the treadmill condition and has potential clinical  
310 significance. These findings suggest that running on this type of treadmill may be

311 associated with an increased risk from injury as rearfoot eversion is implicated in the  
312 aetiology of a number of overuse injuries (Willems et al., 2004, Lee et al ., 2010,  
313 Taunton et al ., 2002 and Duffey et al., 2000). Therefore treadmill runners may be at a  
314 greater risk from overuse syndromes such as tibial stress syndrome, plantar fasciitis  
315 and anterior knee pain (Willems et al., 2004, Lee et al., 2010, Taunton et al., 2002 and  
316 Duffey et al., 2000).

317 A number of previous investigations examining the mechanics of treadmill and  
318 overground locomotion attribute the differences between the two conditions to a lack of  
319 familiarization to the treadmill protocol (Wall and Charteris, 1981). Mastas et al., (2000)  
320 proposes studies reporting significant differences between the two conditions  
321 locomotion have generally put little emphasis on subject familiarisation to treadmill  
322 locomotion and concluded that differences may disappear following an appropriate  
323 accommodation period. The results of this study appear to oppose this claim as a  
324 number of significant differences were observed despite the utilization of a five minute  
325 accommodation period. Furthermore, the findings of the current investigation appear to  
326 be representative and as Matsas et al., (2000) found that reliable kinematic  
327 measurements could be obtained following 4 minutes of treadmill habituation.

328

### 329 *Limitations*

330 The means by which footstrike and toe-off were determined differed from conventional  
331 methods as the treadmill did not feature an integrated force platform. Given this  
332 limitation the stance and swing phases were separated using kinematic data using the  
333 Dingwell et al., (1998) method. A number of methods have been utilized for the  
334 determination of gait events using kinematic data (Alton et al., 1998, Hreljac and

335 Stergiou., 2001, Zeni et al., 2008, O'Connor et al., 2003 and Schache et al., 2001).  
336 However, although these computational methods are repeatable they are known to be  
337 associated with error when contrasted to the gold-standard method using force  
338 platform data (Fellin et al., 2010 and Sinclair et al., 2011).

339 A possible limitation is that this study observed right foot contact only. Bilateral studies  
340 are considered to be more appropriate as symmetry between limbs is unlikely  
341 (Cavanagh and Lafortune, 1980). Another prospective restriction of the current  
342 investigation is that the results are specific exclusively to the treadmill and surface  
343 conditions as well as the velocity of motion and variations in these parameters would  
344 likely cause changes in the runners movement strategy, additional work should  
345 therefore be conducted examining the effect of different treadmills on gait mechanics.

346

### 347 *Conclusions*

348 The results of this study suggest that treadmill should be utilized with caution within  
349 clinical and research settings in terms of its ability to mimic the mechanics of  
350 overground running. Furthermore, given that injury patterns may to differ between the  
351 two conditions it is also recommended that runners consider their primary method of  
352 training when selecting the most appropriate footwear for their needs as treadmill  
353 runners are likely to require footwear with additional medial stability properties, aimed  
354 at reducing rearfoot eversion.

355

356

357



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