

*Citation for published version:*

Squadrone, R, Rodano, R, Hamill, J & Preatoni, E 2015, 'Acute effect of different minimalist shoes on foot strike pattern and kinematics in rearfoot strikers during running', *Journal of Sports Sciences*, vol. 33, no. 11, pp. 1196-1204. <https://doi.org/10.1080/02640414.2014.989534>

*DOI:*

[10.1080/02640414.2014.989534](https://doi.org/10.1080/02640414.2014.989534)

*Publication date:*

2015

*Document Version*

Peer reviewed version

[Link to publication](#)

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1 **TITLE PAGE**

2

3 **Title**

4 Acute effect of different minimalist shoes on foot strike pattern and kinematics in rearfoot  
5 strikers during running

6 **Running Title**

7 Effect of minimalist shoes on running kinematics

8

9 **Word count**

10 [ ]

11

12 **KEYWORDS**

13 [barefoot running, minimalist shoes, rearfoot strikers, running kinematics, footstrike patterns]

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15

16 **ABSTRACT**

17         Despite the growing interest in minimalist shoes no studies have compared the efficacy  
18 of different types of minimalist shoe models in reproducing barefoot running patterns and in  
19 eliciting biomechanical changes that make them differ from standard cushioned running  
20 shoes. The aim of this study was to investigate the acute effects of different footwear models,  
21 marketed as “minimalist” by their manufacturer, on running biomechanics. Six running shoes  
22 marketed as barefoot/minimalist models, a standard cushioned shoe and the barefoot  
23 condition were tested. Foot/shoe-ground pressure and three-dimensional lower limb  
24 kinematics were measured in experienced rearfoot strike runners while they were running at  
25 3.33 m/s on an instrumented treadmill. Physical and mechanical characteristics of shoes  
26 (mass, heel and forefoot sole thickness, shock absorption and flexibility) were measured with  
27 laboratory tests. There were significant changes in foot strike pattern (described by the strike  
28 index and foot contact angle) and spatio-temporal stride characteristics, whereas only some  
29 among the other selected kinematic parameters (i.e. knee angles and hip vertical  
30 displacement) changed accordingly. Different types of minimalist footwear models induced  
31 different changes. It appears that minimalist footwear with lower heel heights and minimal  
32 shock absorption are more effective in replicating barefoot running.

33

34 **KEYWORDS**

35 [barefoot running, minimalist shoes, rearfoot strikers, running kinematics, footstrike patterns]

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## 43 1. INTRODUCTION

44 In the last five years, an increasing number of recreational runners and footwear  
45 manufacturers have shown interest in barefoot running and in footwear designed to mimic the  
46 unshod condition (Langer, 2012; Rothschild, 2012a; Jenkins & Caugthon, 2011; Douglas,  
47 2013). This trend has been fostered by the suggestion that running without the assistance of  
48 modern running shoes might lead to a reduction in the incidence of running-related injuries  
49 (Liebermann et al., 2010). Barefoot running has been a very popular topic in books,  
50 magazines, web sites, as well as in scientific research (e.g. Jenkins & Caugthon, 2011;  
51 Rothschild, 2012b; Hsu, 2012), and almost every major shoemaking company has started  
52 marketing a minimalist or barefoot-like shoe line. New minimalist shoe companies are  
53 continually emerging (Altmann & Davis, 2012a), to the point that in 2011 this market accounted  
54 for 8% of total running shoe sales in North America (Less Shoe, More Sales, Footwear Insight,  
55 2011).

56 The main argument in favour of running either barefoot or using “minimalist” footwear is  
57 that the cushioned heel of modern running shoes may encourage heel-strike patterns and  
58 decrease foot proprioception, thus increasing loading rates and impact forces (Hsu, 2012).  
59 Also, most minimalist shoe manufacturers state that their footwear would promote a more  
60 “natural” running style, where the term “natural” has been associated to how we run without  
61 shoes. In both cases, there is no scientific evidence available to support such statements.

62 Although a formal and specific definition for minimalist shoe is still lacking, there is a  
63 general agreement that minimalist footwear ideally has either less structure, mass, and heel-  
64 toe drop than a heavily cushioned and controlling conventional one, or is more flexible and  
65 less restrictive for foot motion (Hamill, Russell, Gruber, & Miller, 2011). The ambiguity of the  
66 term “minimalist” and the lack of normative guidelines based on biomechanical analyses have  
67 resulted in a myriad of models that are based on different conceptual ideas and approaches.

68 As a consequence, the minimalist category includes: low heel and heel-toe drop footwear (e.g.  
69 Vibram® Fivefingers®, Merrel® Barefoot™ and New Balance® Minimus™); shoes that have  
70 a thicker sole and provide more cushioning (e.g. the Nike® Free™); and, models that seem  
71 to be a compromise between barefoot and traditional racing flat (e.g. Saucony® Kinwara®  
72 and Brooks® Pure™ series).

73 Several studies have assessed biomechanical differences between barefoot and shod  
74 running (De Wit, De Clercq, & Aerts, 2000; Divert, Mornieux, Baur, & Mayer, 2005; Liebermann  
75 et al., 2010; Perl, Daoud, & Lieberman, 2012). However, few have been specifically focused  
76 on minimalist shoe models and their findings appear to be inconsistent., Squadrone and  
77 Gallozzi (2009) showed that spatio-temporal characteristics, lower limb geometry at impact  
78 and peak ground reaction forces while wearing a minimalist shoe were more similar to barefoot  
79 running than to running with conventional shoes. In their study the authors analysed a single  
80 ultra-minimalist shoe model and included only eight subjects familiar with barefoot running. By  
81 analysing ground reaction forces and lower limb kinematics/kinetics in habitually shod runners,  
82 Paquette, Zhang, and Baumgartner (2013) found that lower limb loading rate was greater in  
83 barefoot and in a minimalist shoe compared to standard running shoes. Bonacci et al. (2013)  
84 analysed barefoot running in comparison with three different shod conditions: minimalist shoe,  
85 racing flat and the athlete's regular cushioned shoe. They found significant differences in knee  
86 and ankle kinematics and kinetics between barefoot and shod conditions, but no differences  
87 between the different shoe types. In contrast with Squadrone and Gallozzi (2009) and  
88 Paquette et al. (2013), they concluded that minimalist and lightweight shoes do not change  
89 the biomechanics of highly trained runners in comparison with more conventional shoes.  
90 Finally, Sinclair, Greenhalgh, Brooks, Edmundson, and Hobbs (2013) found significant  
91 differences between barefoot running and running in a minimalist shoe and concluded that the  
92 mechanics of shoes that aim to simulate barefoot movements does not mimic barefoot  
93 locomotion.

94 Methodological factors and the use of different types of minimalist shoes may explain  
95 the discrepancies between studies. Specifically, Squadrone and Gallozzi (2009) and Paquette  
96 et al. (2013) used a Vibram® Fivefingers®, which had a 3.5 mm-rubber sole shoe and offered  
97 very little cushioning properties, whereas Bonacci et al. (2013) and Sinclair et al. (2013)  
98 utilised a Nike® Free™ model, which had a 17 mm-stack height and more cushioning  
99 capability.

100 To the best of our knowledge no studies have directly compared in a single experiment  
101 the efficacy of different types of minimalist shoes in reproducing barefoot running patterns and  
102 in eliciting biomechanical changes that make them differ from standard cushioned running  
103 shoes. The aim of this study was: 1) to investigate the influence of six different footwear  
104 models, marketed as “minimalist” by their manufacturer, on running biomechanics in a group  
105 of rearfoot strike recreational runners; and, 2) to classify these shoes on the basis of their  
106 ability to modify running patterns in comparison with the barefoot and standard cushioned  
107 shoe conditions. We hypothesized that a minimalist shoe with different mechanical and  
108 structural characteristics would induce different changes in foot strike pattern and running  
109 kinematics.

110

## 111 **2. METHODS**

### 112 **2.1 Design**

113 A cross-sectional design was used to study the effect of different shoes (within-group  
114 factor) on a set of biomechanical measures (each one representing a dependent variable) in  
115 running.

116

## 117 **2.2 Participants**

118 Fourteen experienced male recreational runners (mean and SD: age,  $30 \pm 6$  years;  
119 height,  $1.76 \pm 0.08$  m; body mass,  $73 \pm 5$  kg; 10km race time,  $43 \pm 6$  min) were the subjects of  
120 this study. All the participants were used to running more than 45 km/week, had a training  
121 experience wearing minimalist shoes (at least 50% of their training volume) for an average of  
122 2.8 years before the test, and no major injuries for the previous 12 months. Only subjects with  
123 a baseline rearfoot strike pattern were included in the study. Each participant provided written  
124 informed consent before participation in the study, which was approved by the Ethics  
125 committee of the Institute of Sport Medicine and Sport Science (Roma, Italy).

126

## 127 **2.3 Data collection and processing**

128 Eight different experimental conditions were studied: (1) barefoot; (2) cushioned stability  
129 shoe (Saucony® ProGrid™ Guide™4); and five different shoes marketed as minimalist by  
130 their producers, including (3) Newton Running® MV2, (4) New Balance® MR00GB, (5) Nike®  
131 Free™ 3.0V4, (6) Inov8® Bare-X™ 200, (7) Vibram® Fivefingers® Seeya™ and (8) Saucony®  
132 Kinvara™2. All the shoes included in this study were procured on the open market through  
133 retail stores and on-line retailers.

134 The physical and mechanical characteristics of the models (mass, stack height at the  
135 heel and forefoot, heel-toe drop, heel shock-absorption properties and flexibility) were  
136 assessed in the laboratory before the running tests. The measurements were taken on 8.5  
137 men's US size models. Shock-absorption properties were measured at the heel.

138 In the 10 days prior to testing, all the subjects were required to come to the laboratory  
139 and complete at least three running bouts of 8 minutes in each condition in order to familiarise  
140 with the experimental set-up and the different shoe types.

141 During the test session each participant was asked to perform running bouts of 3 minutes  
142 at 3.33 m/s using his preferred cadence and foot striking technique. A rest period of 5 minutes  
143 separated the bouts and the order of shoe models was selected randomly across runners.

144 The pressure distribution at the shoe-ground interface and the right lower limb kinematics were  
145 simultaneously collected during the last 20 s of each running trial.

146 The Zebris® FDM-T (Germany) instrumented treadmill was used to measure the  
147 pressure distribution at the foot-ground or shoe-ground interface. Pressure data were sampled  
148 at 180 Hz and the threshold level was set at 5 N/sensor.

149 Stride length (defined as the distance covered with each stride), stride frequency,  
150 contact and flight times, and total vertical force occurring during each stance phase were  
151 estimated from pressure data. The strike index was calculated as the ratio of the centre of  
152 pressure location at foot strike relative to the length of the foot (Cavanagh & LaFortune, 1980).  
153 Conventionally a strike index of 0–33% indicates a rearfoot striker, 34–67% a midfoot striker,  
154 and 68–100% a forefoot striker.

155 Retro-reflective markers (10 mm diameter) were fixed over the following anatomical  
156 landmarks of the right lower limbs: lateral and medial femoral epicondyle; lateral and medial  
157 calcaneous; lateral and medial malleolus; first and fifth metatarsal heads. Two additional  
158 markers were placed bilaterally on the greater trochanters. Excluding the markers placed over  
159 the calcaneous and metatarsal heads, all marker placements were unchanged between  
160 conditions. Three-dimensional positions of each marker were captured by eight digital infrared  
161 cameras (BTS® Smart-E, BTS Bioengineering, Milan, Italy) sampling at 120 Hz. After  
162 assessing the frequency at which 95% of the signal power was below, the signals were filtered  
163 using a low-pass fourth-order zero-lag Butterworth filter with a cut-off frequency of 10 Hz  
164 (Sinclair et al., 2013). Marker positions were processed to estimate a number of variables  
165 (Figure 1), including: the knee angle and the foot angle at ground contact with respect to the  
166 horizontal, the peak knee flexion angle during stance, the knee flexion ROM during stance,  
167 the stride angle (i.e. the maximum opening between the front and rear thigh), the over-stride  
168 angle (i.e. the angle between the front leg and the vertical at ground contact) and the vertical  
169 hip displacement, which was calculated as the difference between the maximum and minimum  
170 vertical displacement of the marker placed on the greater trochanter.



171

172

---INSERT FIGURE 1 ABOUT HERE---

173

#### 174 **2.4 Statistical analysis**

175 Statistical analysis was carried out with SPSS® software (IBM®, New York, USA).

176 Average measures from individual participants were used to characterise each shoe condition

177 through descriptive statistics. A one-way repeated-measures ANOVA was used to determine

178 the effects of shoe-types on running parameters. Effect sizes were assessed by calculating

179 eta-square ( $\eta^2$ ). Where appropriate, a Tukey's test was used in the post-hoc analysis to assess

180 differences between conditions. Significance was accepted at  $p < 0.05$  level. For significant

181 post hoc findings the percentage mean difference, 95% CIs and standardised mean difference

182 (SMD) were also calculated.

183



209 Foot condition also had a main effect on stride frequency ( $F(7,91)=17.88$ ,  $p<0.001$ ,  
210  $\eta^2=0.64$ ), stride length ( $F(7,91)=17.67$ ,  $p<0.001$ ,  $\eta^2=0.63$ ), step time ( $F(7,91)=16.72$ ,  $p<0.001$ ,  
211  $\eta^2=0.61$ ) and contact time ( $F(7,91)=16.23$ ,  $p<0.001$ ,  $\eta^2=0.61$ ), with post-hoc analysis showing  
212 different subgroup differences depending on the variable under analysis.

213 Stride length reduced significantly when barefoot compared with all shod conditions  
214 (range of percentage difference: 1.7%-3.5%,  $p<0.001$ ,  $SMD=0.9-1.8$ ; Table 2). Step time, and  
215 contact time also reduced (1.8%-3.6%,  $p<0.001$ ,  $SMD=1.2-2$  and 1.6%-7.5%,  $p<0.001$ ,  
216  $SMD=0.9-4.1$ , respectively) comparing barefoot with the shod conditions. Conversely, stride  
217 frequency showed an opposite trend with significant higher values when running barefoot (1.6-  
218 4.1%,  $p<0.05$ ,  $SMD=0.7-1.4$ ; Table 2). Among the minimalist models, only Vibram Fivefingers  
219 and Newton Running shoe had significant higher stride frequency than the cushioned shoe  
220 (2.4%, CI 1% to 3.8%,  $p=0.000$ ,  $SMD=0.9$ , and 1.8%, CI 0.5% to 3.3,  $p=0.016$ ,  $SMD=0.7$ ,  
221 respectively).

222 The minimalist shoes appeared to be clustered into two subgroups based on stride  
223 frequency, stride length and step time: 1) Newton Running and Vibram Fivefingers shoe; and  
224 2) Saucony, Nike, New Balance, and Inov8 shoe. Stride frequency was ~15% higher in the  
225 first group, whereas stride length and step time were ~15% and 18% lower. Contact times  
226 were in ascending order in the following subgroups: 1) Vibram Fivefingers; 2) New Balance;  
227 3) Inov8 and Newton Running; 4) Saucony and Nike shoe.

228 Knee contact angle ( $F(7,91)=4.07$ ,  $p<0.001$ ,  $\eta^2=0.40$ ), knee ROM ( $F(7,91)=5.41$ ,  
229  $p<0.001$ ,  $\eta^2=0.42$ ), and hip vertical displacement ( $F(7,91)=5.72$ ,  $p<0.001$ ,  $\eta^2=0.42$ ) showed  
230 main effects for running conditions, whereas stride angle, overstride angle and peak knee  
231 flexion appeared invariant to the type of footwear (Table 2).

232 In the cushioned shoe and in the Nike shoe, knee angle at heel strike was significantly  
233 more extended than in barefoot (1.7%, CI 0.7% to 2.7%;  $p=0.000$ ,  $SMD=0.9$ , and 1.5%, CI  
234 0.5% to 2.5%,  $p=0.007$ ,  $SMD=0.8$ , respectively). Comparing the minimalist models, the knee  
235 was 1.1% (CI 0.2% to 2%,  $p=0.034$ ,  $SMD=0.6$ ) more flexed when running in Inov8 than in Nike

236 shoe. Knee ROM was lower in barefoot and higher in cushioned model, with Inov8, Vibram  
237 Fivefingers and New Balance shoe characterised by values significantly lower than in  
238 cushioned shoe (8.6%,  $p=0.01$ , SMD=0.6, 9%,  $p=0.02$ , SMD=0.6 and 7.8%,  $p=0.02$ ,  
239 SMD=0.56, respectively) and by a non-significant trend of higher values compared to barefoot.  
240 The Nike and Saucony shoes had increased vertical hip displacement than the barefoot  
241 condition and all the other minimalist models.

#### 242 **4. DISCUSSION**

243 The purpose of this study was twofold: 1) to determine the influence of different  
244 minimalist footwear models on running biomechanics; and 2) to classify these shoes based  
245 on their ability to modify running patterns compared to running barefoot and a standard  
246 cushioned shoe. We hypothesized that the use of minimalist shoes would result in acute  
247 changes in both foot strike pattern and kinematic variables and that the extent of these  
248 changes depends on the different types of shoes. This hypothesis was partially supported with  
249 changes in foot strike pattern (described by the strike index and foot contact angle) and spatio-  
250 temporal stride characteristics, while only some among the other selected kinematic  
251 parameters (i.e. knee angles and hip vertical displacement) changed accordingly.

252 Not all the minimalist footwear selected behaved similarly. Across minimalist shod  
253 conditions the number of parameters significantly similar to barefoot ranged from 3 to 8 and  
254 those different from the cushioned shoe from 0 to 8. None of the models induced immediate  
255 adjustments identical to barefoot while some models (Vibram Fivefingers Seeya, New Balance  
256 MR00GB and Inov8-X 200) appeared to be more effective than others (Newton Running MV2,  
257 Saucony Kinvara 2 and Nike Free 3.0V4) in reproducing barefoot-like running patterns and in  
258 eliciting changes that make them differ from standard cushioned running shoes.

259 These results confirm and extend what was found by prior studies on minimalist footwear  
260 and help to explain the apparent inconsistency of some of them which came to different  
261 conclusions regarding the efficacy of minimalist shoes. Specifically, our findings on Nike Free

262 model agree with Willy and Davis (2013) who concluded that running in this shoe failed to  
263 result in changes in spatio-temporal parameters when compared with running in a standard  
264 running shoe. The results also agree with Bonacci et al. (2013) and Sinclair et al. (2013), who  
265 concluded that the mechanics of this footwear does not appear to closely mimic the kinematics  
266 of barefoot locomotion in experienced runners. In addition, our findings on the Vibram  
267 Fivefingers shoe confirm, even for rearfoot strikers, the findings of Squadrone & Gallozzi  
268 (2009), that found that this type of shoes have no significant effect on barefoot running  
269 kinematics.

270 In general, although all runners in the current study were classified as rearfoot runners  
271 according to the strike index (i.e. <33%), it appeared that, in the traditional cushioned shoe  
272 the initial contact was more towards the heel area than it was in the barefoot condition.  
273 Runners seemed to progress towards a more midfoot strike while barefoot running, and this  
274 was confirmed by the foot contact angle, which was ~40% less dorsiflexed in barefoot than in  
275 cushioned shoe. Similar adjustments have been reported by previous studies (De Wit et al.,  
276 2000; Squadrone & Gallozzi, 2009; Liebermann et al., 2010; Hamill et al., 2011; Bonacci et  
277 al., 2013; Horvais & Samozino, 2013) and are not particularly surprising. In a recent study,  
278 Paquette et al. (2013) found that the strike index was greater in barefoot condition and in  
279 Vibram Fivefingers than in cushioned shoes, in both rearfoot and midfoot striker runners. A  
280 flatter foot placement would disperse pressure to a larger surface area, effectively reducing  
281 the acute force applied to the heel region. Hamill et al. (2011) reported that the change in  
282 footfall pattern from a shod cushioned condition to barefoot towards a more midfoot strike  
283 could be the result of pain from landing on the heel, particularly on a hard surface. This  
284 assumption agrees with the findings of De Wit et al. (2000) and Divert et al. (2005) who  
285 reported lower peak pressure at impact while running barefoot.

286 With minimalist footwear, the strike index values were between the cushioned shoe  
287 (closer to the heel) and the barefoot condition (closer to a midfoot strike) with some footwear  
288 (e.g. Group 1 - Newton Running, Saucony, Nike shoe) closer to a definitive rearfoot strike and

289 others (e.g. Group 2 - New Balance, Inov8, Vibram Fivefingers shoe) closer to a midfoot strike.  
290 These differences can be explained in terms of the construction of the two groups of minimalist  
291 footwear. Group 1 shoes had a greater heel stack height (22 to 26 mm) than those of Group  
292 2 (7 to 13 mm). Similar to the reasoning for the difference in the cushioned shoe and the  
293 barefoot condition, the greater heel height resulted in more material to protect the heel on  
294 impact in Group 1 shoes, whereas there was insufficient heel material in Group 2 shoes to  
295 prevent the possible heel pain at foot contact. The result is a more forward (i.e. closer to  
296 midfoot) contact in Group 2 shoes. This interpretation is reinforced by the results of shock  
297 absorption tests where the shoes of Group 1 showed shock absorption characteristics better  
298 than those of Group 2 and similar to the cushioned shoe.

299         Once again, these modifications in foot strike pattern were confirmed by the kinematics  
300 of the foot contact angle, which ranked the shoes and clustered them into the same subgroups  
301 as the strike index. The group with shoes of heel heights closer to the cushioned shoe (Newton  
302 Running, Saucony and Nike shoe) showed a clear trend towards a more dorsiflexed foot  
303 position. The foot contact angle may thus be considered a good predictor of the strike index  
304 when force platform data are not available, as demonstrated by Altman and Davis (2012b) in  
305 a study correlating the two measures.

306         The results for the spatio-temporal differences, while presenting an overall difference  
307 among footwear conditions, were not as clear. The reduction of stride length, step time and  
308 contact time in running barefoot compared with all shod conditions is not surprising and  
309 confirms that spatio-temporal variables are influenced by environmental changes such as the  
310 foot-ground interface (De Wit et al., 2000). It is also apparent that when these parameters  
311 were reduced, stride frequency was concomitantly increased to maintain a constant speed  
312 during barefoot running.

313         The results from our study are in line with those previously found by Divert et al. (2005)  
314 and Squadrone & Gallozzi (2009) in sub-elite athletes running on a treadmill at the same  
315 speed, and by Bonacci et al. (2013) in highly trained runners. The runners analysed by those  
316 authors, progressively adopted shorter stride lengths and higher stride frequencies when

317 running condition changes from cushioned to minimalist and from minimalist to barefoot.  
318 Reduced stride length has been shown to decrease impact characteristics and to increase  
319 shock attenuation (Derrick, Hamill, & Caldwell, 1998; Mercer, Vance, Hreljac, & Hamill, 2002).  
320 Therefore, once again, the attempt to reduce the possible pain caused by the heel-ground  
321 contact while barefoot or in minimalist footwear would suggest these alterations.

322         However, compared to foot strike pattern, the differences in spatio-temporal measures  
323 between the minimalist models we analysed were smaller in magnitude and appeared to be  
324 minimally influenced by their geometry and mechanical characteristics. For example, two  
325 shoes with different construction features, one with a thinner midsole (Vibram Fivefingers  
326 shoe) and the other with thicker midsole and higher shock-absorption properties (Newton  
327 Running shoe) showed a relatively similar behaviour, with greater stride frequencies than both  
328 the cushioned shoe and the other minimalist models. The lack of relation between the  
329 geometry of the sole/midsole and stride frequency, which was also found by Horvais and  
330 Samozino (2013), may be caused by the relatively low impact forces generated by the  
331 combination of the moderate running speed used in these studies with the compliance of the  
332 treadmill belt.

333         The knee contact angle was influenced by footwear conditions. The knee was more  
334 extended in the footwear with greater heel thickness than in the lower heel heights and  
335 barefoot. Such a postural adaptation is thought to increase landing stiffness (Denoth, 1986;  
336 Farley, Houdijk, Van Strien, & Louie, 1998). It has been suggested that in running, the knee  
337 acts as a major shock absorber to attenuate the shock of the foot-ground contact (Hamill,  
338 Gruber, & Derrick, 2012) and to regulate leg stiffness in rearfoot strikers. In footwear with an  
339 elevated heel, the higher heel height can also act to attenuate shock. Even though we did not  
340 measure joint stiffness, our finding can be interpreted as a desire to maintain the same  
341 combined leg-shoe stiffness at impact as heel height and shock absorption of shoes increases  
342 (Hardin, van den Bogert, & Hamill, 2004).

343         Knee ROM increased in the shoes with higher heel heights. This is consistent with prior  
344 works that found a reduced knee ROM while barefoot compared to minimalist shoes such as

345 Nike Free (Bonacci et. al, 2013) and standard cushioned shoes (De Vit et al., 2000). Lower  
346 knee ROM was also found by Squadrone and Gallozzi (2009) while running in a low heel  
347 minimalist shoe compared to a protective running shoe. The higher knee ROM in the shoes  
348 with thicker heel height may be explained by the greater contact time in these conditions  
349 compared to the less thick heel shoes and barefoot, which would provide more time to  
350 increase knee flexion during stance. In addition, the trend to a more midfoot contact with the  
351 thicker shoes may have increased the involvement of the ankle in absorbing energy at impact  
352 reducing the need of higher knee flexion.

353 Finally, with hip vertical displacement, this study shows that the thicker the heel material  
354 in a running shoe, the greater the hip displacement. This result could be explained with the  
355 straighter support leg on contact associated with this condition, which place the hip in a higher  
356 vertical position and with the more knee flexion ROM in the stance.

357

## 358 **5. CONCLUSION**

359 This study implies that heel strike runners do respond to minimalist footwear by altering  
360 certain biomechanical parameters compared to barefoot and standard cushioned shoe  
361 conditions. The magnitude of these acute adaptations varied across the different types of  
362 minimalist footwear models. In particular, it was clear that in the footwear with less material  
363 and cushioning under the heel there was a significant move towards a more midfoot footfall  
364 pattern. We concluded that minimalist footwear with extreme lower heel heights and less  
365 shock absorption capabilities induce an alteration in footfall pattern. If we define “minimalist”  
366 as the quality of replicating barefoot running conditions, then heel height and shock absorption  
367 characteristics seem to be the most prominent parameter to be taken into consideration. When  
368 transitioning from standard running shoes to minimalist footwear runners should consider the  
369 possibility and the impact of these changes regarding injury risk. Future studies should focus  
370 on 1) the long-term adaptation to minimalist shoes and 2) the quantification of the effect of



371 each element of the shoe design and of its mechanical factors on foot strike pattern and  
372 running kinematics.

373

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Table 1. Physical and mechanical characteristics of the analysed shoes.

	Mass (g)	Forefoot stack height (mm)	Heel stack height (mm)	Heel- toe drop (mm)	Shock absorption (m/s <sup>2</sup> )	Flexibility (N*m)	Comments/claims/ description of the producers
Cushioned shoe	330	28	42.0	14.0	9.0	5.9	
Saucony Kinvara 2	215	23	28.5	5.5	12.0	3.3	Was marketed as a minimally constructed, lightweight and responsive shoe that fits like a glove and allows the foot to move freely throughout the whole gait cycle
Nike Free 3.0V4	213	17	26.0	9.0	10.0	0.9	Was marketed as a minimalist shoe that can provide a “barefoot ride”.
Inov8 Bare-X 200	200	8	8.0	0.0	14.7	0.3	Was marketed as a pure minimalist shoe designed for performing “as nature intended”.
Newton Running MV2	171	22	22.0	0.0	10.7	1.5	Was marketed as a minimalist shoe because it would allow the foot to move more naturally than standard shoes. Some retailers include it in the racing flat category
New Balance MR00GB	165	12	13.0	1.0	13.8	0.8	Was marketed as a minimalist shoe that allows for a “closer barefoot running experience”.
Vibram Fivefingers Seeya	127	7	7.0	0.0	19.0	0.2	Was marketed as a minimalist shoe that would allow to mimic the barefoot condition while still providing protection.

*Note:* Forefoot stack height and heel stack height refer to plantar surface-ground distance measured at the ball of the foot and at the centre of the heel respectively, and were measured by a high precision calliper. Heel-toe drop was calculated as the difference between heel and forefoot stack height. The heel dynamic shock absorption properties of the shoes were determined by a dynamic shock absorption test machine (Falling Tester IG/MPS-C, Giuliani Tecnologie: Scientific Instruments Division, Torino, Italy). A low deceleration value indicates good shock absorption characteristics. Flexibility was assessed measuring the shoe longitudinal bending stiffness by a dynamic footwear stiffness test machine (Rigidity Test IG/CRS-S, Giuliani Tecnologie: Scientific Instruments Division, Torino, Italy). A low stiffness indicates a high level of footwear flexibility.

Table 2. Foot strike, spatio-temporal stride and kinematic variables (mean±SD) for the different foot conditions.

	<b>Barefoot</b>	Vibram Fivefingers Seeya	Inov8 Bare-X 200	New Balance MR00G B	Newton Running MV2	Saucony Kinvara 2	Nike Free 3.0V4	<b>Cushion ed shoe</b>
<b>Foot strike variables</b>								
Strike index (%)	27.0±4.6	25.5±4.4 # b	24.5±5.2 # b	25.4±5.0 # b	21.0±4.9 * a	19.6±5.2 * a	19.9±5.4 * a	18.6±6.2 *
Foot angle at contact	7.3±3.4	6.9±3.2 # a	7.6±3.2 # a	8.0±3.1 # a	10.7±3.2 * b	11.8±3.1 * b	12.3±2.7 * b	12.1±2.9 *
<b>Spatio-temporal stride variables</b>								
Stride frequency (step/min)	86.8±2.3	85.4±2.0 * # b	83.6±2.2 * a	84.1±2.1 * a	84.9±1.8 *# b	84.0±1.9 * a	83.7±2.2 * a	83.4±2.4 *
Stride length (m)	2.30±0.0 4	2.34±0.0 4*# a	2.38±0.0 5* b	2.37±0.0 4* b	2.35±0.0 5* a	2.37±0.0 4* b	2.38±0.0 5* b	2.38±0.0 5*
Step time (ms)	346±5	352±5*# a	358±6* b	357±5* b	354±6*# a	357±5* b	358±6* b	358±6* b
Contact time (ms)	234±4	238±4*# a	246±4*# c	242±4*# b	247±4* #c	250±4* d	252±4* d	251±4* d
<b>Kinematic variables</b>								
Stride angle (°)	73.2±4.6	72.6±4.7	73.4±4.6	74.3±4.5	74.2±4.4	73.3±4.2	72.5±4.7	74.5±4.8
Overstride angle (°)	7.2±3.4	8.1±3.5	7.7±3.6	7.5±3.4	8.8±3.6	8.6±3.5	8.5±3.6	8.6±3.4
Knee contact angle (°)	163.8±3.4	165.1±3.3 2 a,b	164.5±3.3 # a	165.2±3.3 3 a,b	165.4±3.3 3 a,b	165.6±3.3 2 a,b	166.3±3.3 1*b	166.6±3.3 2*
Peak stance knee flex angle (°)	138.8±4.6	138.5±4.3 3	137.9±4.4 5	138.2±4.4 7	138.0±4.4 6	137.6±4.4 4	137.4±4.4 2	137.5±4.4 2
Knee ROM stance phase (°)	25.1±4.2	26.7±4.2 4.2 #a	26.6±4.2 4.1 #a	26.9±4.2 3.8 #a	27.4±4.0 *a	28.0±4.0 4.1*a,b	28.9±4.0 4*b	29.0±4.0 *
Hip vertical displacement (mm)	8.0±3.2	8.2±3.4 #a	7.8±3.6 #a	7.3±3.4 #a	9±3.6 a	11.5±3.2 *b	10.8±3.3 *b	10.8±3.4 *
Number of variables significantly similar to barefoot (n)	--	8	8	8	5	4	3	--
Number of variables significantly different from cushioned model (n)	--	8	6	5	3	0	0	--

\* Significantly different from Barefoot. # Significantly different from the Cushioned shoe. Letters are linked to the trend in the values (from lower to higher) and separate minimalist shoes into statistically homogenous subgroups within row: means with the same letters were not significant different (p>0.05).