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Research article

The Association Between Rearfoot Motion While Barefoot and Shod in Different Types of Running Shoes in Recreational Runners

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Abstract

The rearfoot angle (RFA) is a biomechanical variable widely used to determine the rearfoot motion (RM). Shoe manufacturers began to develop running shoes with RM control that would supposedly alter foot-ground interaction mechanics and neutralize excessive pronation or supination; moreover, some studies have not shown differences in rearfoot motion in shod condition compared to barefoot. This study intended to answer three questions: Do the shoes runners wear correspond to their respective barefoot RM? Does the eversion angle change during shod running, regardless the shoes worn? Can footwear designed for a specific RM (supination, pronation, neutral) correct or neutralize the eversion angle of runners? One hundred and eleven runners (38.6 ± 9.7years; 74.9 ± 12.0kg; 1.74 ± 0.08 m), who ran an average of 32 ± 17km/week, were included in this cross-sectional study. They had their RFA measured by a motion capture system when running barefoot and wearing their habitual running shoes (shod condition). Chi-squared test was used to assess associations between barefoot and shod condition and RFA was compared between conditions using Wilcoxon tests ($p = 0.05$). There was no association between the type of running shoe and barefoot RM ($p > 0.05$). There was an association between RFA when barefoot and when shod ($p < 0.05$). Among all participants classified as neutral, 61% continued to exhibit a normal/neutral RFA when wearing their habitual shoes. Among the overpronators, 100% showed a change in the RM to either normal or supinator. Among the participants classified as supinators, 62% exhibited normal pronation when shod even without using the appropriate footwear, claimed by the manufacturer. Only 44.1% of the sample chose the correct running shoe for their barefoot RM. The majority of runners did not choose their shoes designed for their natural type of RM. The rearfoot eversion angle changed an average 4 degrees when running shod and the RM barefoot altered quite a lot when using a running shoe. The running shoes did not correct the pronation detected barefoot, as claimed by the manufacturers.

Key words: Running, footwear, biomechanics, rearfoot motion, kinematics.

Introduction

In the 1970s, manufacturers began to produce different types of running shoes aimed at reducing mechanical overload or altering foot-ground interaction using motion control mechanisms, with a view to lowering the risk of sports-related lower extremity injuries (Lieberman et al., 2010). Running, currently one of the most popular sports, has a 20 to 79% lower extremity injury rate (van Gent et al., 2007), with one of the risk factors being rearfoot kinematics (Chang et al., 2014; Cheung et al., 2010; Morley et al., 2010; Rabbito et al., 2011; Willems et al., 2006). More specifically, over pronation has been associated with stress fractures, plantar fasciitis, and lower limb pain in runners, resulting from greater peak rearfoot eversion, increased excursion eversion and maximal eversion velocity (Chang et al., 2014; Morley et al., 2010; Rabbito et al., 2011; Willems et al., 2006), while over supination has been linked to leg injuries, resulting from increased leg stiffness and greater impact force (Williams et al., 2004).

In an effort to mitigate the rise of leg injuries, in the 1960s, shoe manufacturers started developing running shoes with rearfoot motion control that would supposedly alter the mechanics of the foot-ground interaction and neutralize excessive pronation or supination (Willy and Davis, 2014). However, the relationship between abnormal RM, injury incidence rates and choosing the right running shoes has yet to be elucidated (van Mechelen, 1992; Morley et al., 2010; Taunton et al., 2003).

The rearfoot angle (RFA) is a biomechanical variable widely used to determine the rearfoot motion, namely pronation, neutral or supination (Song et al., 1996). Specifically, pronation, which is the main focus of the current study, constitutes a complex combination of movements such as ankle dorsiflexion, forefoot abduction, and subtalar eversion. The movement of the subtalar joint at the rearfoot is deemed independent from the one at the forefoot (Perry and Lafortune, 1995; Stacoff et al., 1990). In a study that investigated foot kinematics during running using Principal Component Analysis, it was shown that different joints and regions of the foot should be assessed as separate variables to represent RM, as they were not inter-correlated (Behling et al. 2019). During running, supination occurs at initial contact in the stance phase and is immediately followed by pronation, which might absorb the impact forces. Without pronation, these forces would have to be absorbed suddenly and directly by the support structures, causing problems related to excessive stress. However, there has been a discussion that the medial peak occurs after the lateral peak and before maximum eversion (Morley et al, 2010), thus maybe the pronation is not capable of absorbing the impact forces, since the peak pronation occurs later than the impact (Behling et al. 2019). Finally, the rearfoot begins to supinate again and the foot becomes more rigid and stable (Dugan and Bhat, 2005).

As such, the study intended to answer three questions: (i) Do the shoes runners wear correspond to their respective barefoot rearfoot motion? (ii) Does the eversion angle change during shod running, regardless of the shoes

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worn? (iii) Can footwear designed for a specific rearfoot motion correct or neutralize the eversion angle of runners? The research hypotheses are that (i) runners choose footwear compatible with their rearfoot motion based on subjective perception, (ii) shoes alter the kinematics of the eversion angle in relation to barefoot running, and (iii) choosing footwear specially designed for certain types of rearfoot motion can neutralize excessive eversion.

Methods

Participants and study design

This was a cross-sectional study with 111 recreational runners (81 men and 30 women) aged 38.6 ± 9.7 years (74.9 ± 12.0kg, 1.74 ± 0.08 m), who ran an average of 3.4 ± 1.0 times a week and 31.8 ± 16.6 km a week, and could comfortably run at 10km/h on a treadmill ergometer. Inclusion criteria were no musculoskeletal injuries for at least 6 months prior to the tests, orthopedic leg surgery or degenerative conditions such as osteoarthrosis and chondromalacia (*Runner´s knee*). The study protocol was approved by the local institutional Ethics committee granted full ethical approval (CAAE: 41171215.7.0000.0065). All participants were asked to read and sign a consent form.

Instruments and procedures

Running kinematics was assessed with participants running barefoot and shod on a treadmill ergometer (HPX 40, Total Health, Brazil) surrounded by 6 infrared cameras at 120Hz (Vicon Motion System Ltd., Oxford Metrics, UK). In order to minimize the variability of foot-ankle segmental motion in running, the subjects kept their self-selected speed during all the assessments (Queen et al., 2006). The self-selected speeds for each participant were the same speed in both conditions (mean speed 9.86km/h [95%CI: 9.75 to 9.96]). Barefoot data acquisition aimed to classify the natural rearfoot motion of the runner without the potential effects of shoes on foot mechanics (Altman and Davis, 2012). At the beginning of the study, all runners were randomly assigned to their first set of measurements – barefoot or shod condition. Both conditions were recorded in the same day.

A marker set consisting on eight reflexive-passive markers (14mm diameter) placed on both subject's foot and shoes (Cheung et al., 2007; 2011; Clermont et al., 2017; Kernozek et al., 1990; Kong et al., 2011; Kosonen et al., 2017; McClay and Manal, 1998; Morley et al., 2010), respectively for the barefoot and shod conditions. Four markers were placed on each lower extremity: one on the Achilles tendon between the malleoli (TG); one 15 cm above TG at the center of the leg (AG), immediately below the gastrocnemius muscle; a third and fourth markers on the upper (CP) and lower posterior (CD) surfaces of the calcaneus, respectively, when the subject was barefoot, or at the same height but on the shoe when they were shod (Reinschmidt et al., 1997) (Figure 1).

Each participant ran for 5 minutes on a treadmill at the self-selected speed for habituation, and the last minute was recorded for each condition (barefoot and shod) to analyze both feet. The footwear used in the shod condition was the habitual running shoes of the subjects, with fewer than 6 months use and less than 500 km run (Wang et al., 2010). The footwear worn included cushioned, motion control and stability shoes (Richards et al., 2009), produced by Adidas, Asics, Mizuno, Nike, Olympikus, Saucony among others (supplementary material 1). The running shoes were covered with strips of surgical tape to make the markers more easily visible.

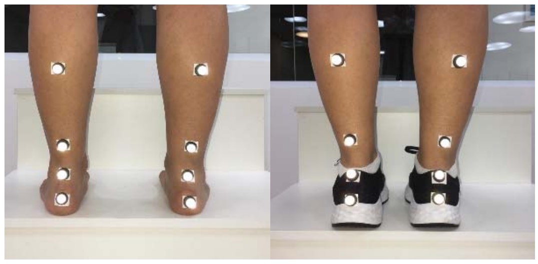

Figure 1. Location of the markers in both condition.

Supplementary material 1. Type of shoes and manufactures.

Manufacturer	Specif Model	Quantitative
Adidas	Adidas Durano	2
	Adidas Boost	5
	Adidas Adiprene+	1
Asics	Asics GEL-Sendai	1
	Asics Noosa	8
	Asics GEL- Nimbus	14
	Asics GEL - Kayano	15
	Asics GEL Kinsei	4
	Asics GT	4
	Asics GEL - Cumulus	3
	Asics GEL - Pulse	3
	Asics GEL - Quantum	1
	Asics GEL - Kinetic	1
Brooks	Brooks Glycerin	2
Merrel	Merrell	1
Mizuno	Mizuno Wave	13
	Mizuno Prophecy	3
Nike	Nike Zoom Streak	1
	Nike Vomero	3
	Nike Free Run	5
	Nike Air Max 360	1
	Nike Lunarlon	2
	Nike Lunarglide	3
	Nike Flyknit Lunar One	1
	Nike Flywire	1
	Nike Structure	1
Olympikus	Olympikus tube tech	1
Pearl Izumi	Pearl Izumi Tri N2	1
Spira Stinger	Spira Stinger	1
Saucony	Saucony Kinvara	3
	Saucony Fastwitch	1
	Saucony Guide	1
	Saucony Cortana	1
Skechers	Go run 3	1
Swiss Engineering	Cloud	1
Kalenji	Kalenji	1

The marker positions and rearfoot angle were analyzed in Visual 3D software (C-Motion, USA). The kinematic data was processed based on residual analysis on kinematic data (Winter and Patla, 1997) using a zero-lag, digital fifth-order butterworth filter, low-pass filter with cutoff frequency of 6 Hz.

The outcome was the maximum eversion angle in the whole stance phase of running. The three-dimensional coordinates (x,y,z) of each marker formed two vectors. The two proximal markers (TC and AG) formed one vector (Va) and the two distal markers (CP and CD) formed another vector (Vb). Thus, the rearfoot eversion angle was defined by the angle of intersection between these two vectors, using the following equation: arc sin = (Va . Vb/ IVaI x IVbI) (Reinschmidt et al., 1997). The values in degrees were taken from a normalized time series (0 – 100%) based on stance phase time of each participant.

In the present study, 0 to 7 degrees was classified as excessive supination (underpronation), 8 to 15 degrees as neutral, and values greater than 15 degrees as excessive pronation (overpronation) (McClay and Manal, 1998). There was no significant difference ($p > 0.05$) in pronation angle between the right and left foot for both condition assessed (barefoot and shod). Thus, both feet were analyzed for each subject, in line with the studies of Nielsen et al. (2014) and Wezenbeek et al. (2017), totalizing a sample of 222 feet.

Statistical analysis

The chi-squared test was used to assess the following associations: (1) between the chosen running shoe and the shoe category defined by the manufacturer, and (2) between barefoot and shod rearfoot motion. Data distribution was not confirmed by the Shapiro-Wilk test and the kinematic variable (eversion angle) was therefore compared in the barefoot and shod conditions (conventional running shoes) for each type of rearfoot motion, using the Wilcoxon signed-rank test (alpha = 0.05) and Statistica software (version 7). Cohen's d effect size and effect size (*r*) were calculated. Effects between 0.2 and 0.5 were considered small, between 0.5 and 0.8 medium, and above 0.8 large (Lakens, 2013).

Results

RFA analysis of the 222 bare feet resulted in a sample consisting of 5 overpronators, 118 normal pronators (neutral) and 99 supinators.

The chi-squared test showed no association between the type of running shoe and barefoot rearfoot motion ($p > 0.05$). As such, only 31.5% of those with normal pronation when barefoot wore neutral running shoes, while the remaining 68.5% used shoes designed for supinators or overpronators. Fifty percent of those classified as overpronators wore running shoes designed for this purpose. Of the 108 feet classified as supinators, only 44 used shoes geared toward their rearfoot motion (Table 1).

The chi-squared test indicated an association between barefoot and shod runners for the RFA ($p < 0.05$). Of the feet classified as neutral, 61% continued to exhibit a normal RFA when wearing their habitual running shoes. Although only a small number of the sample were overpronators, 100% showed a change in rearfoot motion to supination (33%) or neutral (66%). Of the participants classified as supinators when barefoot, 62% exhibited normal pronation when shod even without using the appropriate footwear (Table 2).

Table 3. **Effect of running shoes based on the manufacturers' classification in subjects who chose the appropriate shoe for their rearfoot motion.**

Running shoe classification	Effect (%) YES
Neutral	38.88
Overpronation	83.33
Supination	25.00

Only 44.1% of the sample chose the correct running shoe for their barefoot rearfoot motion. Table 3 demonstrates the effect of shoes on rearfoot motion, determined based on the manufacturers' classification. As such, the goal of neutral running shoes was to maintain the RFA within a normal range, while those for overpronators and supinators should correct the RFA to neutral. Despite the small sample size, shoes designed for overpronators had a positive effect on changing the RFA, whereas those for supinators and normal pronators did not show the same neutralizing effect. However, only 38 and 25% of running shoes for supinators and normal pronators maintained the eversion angle within a neutral range.

Table 1. **Association between running shoe classification according to the manufacturer and barefoot rearfoot motion.**

Barefoot rearfoot motion	Running shoe classification			χ2	p-value
	Neutral	Supination	Overpronation		
Neutral	31.5%	31.5%	37.0%	4.058	0.398
Overpronator	16.7%	33.3%	50.0%		
Supinator	32.4%	40.7%	26.9%		

Table 2. **Association between rearfoot motion in barefoot and shod runners.**

Barefoot rearfoot motion	Shod rearfoot motion			χ2	p-value
	Neutral	Supinator	Overpronator		
Neutral	61.1%	26.9%	12.0%	17.870	0.001
Overpronator	33.3%	66.7%	0.0%		
Supinator	62.0%	13.0%	25.0%		

The results indicate a quantitative difference in rearfoot eversion angles in barefoot and shod runners for the total sample (n = 222) ($p < 0.01$), with an average increase of 4 degrees when participants wore shoes as opposed to running barefoot. The Wilcoxon nonparametric test (alpha = 0.05) also revealed statistically significant differences for the neutral individuals (Table 4).

Table 4. Descriptive analysis of means (standard deviation) and p values in barefoot and shod runners for all participants and when separated into subgroups according to rearfoot motion.

Rearfoot angle (degrees)	Barefoot	Shod	p-value
All participants	7.85 (3.43)	12.08 (4.46)	<0.001*
Normals	10.10 (1.98)	11.81 (2.10)	<0.001*
Supinators	5.12 (3.35)	5.66 (4.54)	0.74
Overpronators	16.67 (0.98)	18.36 (1.98)	0.22

* Statistically significant difference between the two conditions ($p < 0.05$).

Discussion

To minimize the risk of injury, runners usually choose to wear shoes specially designed for their type of rearfoot motion, since overpronation has been linked to running-related injuries (lower leg pain and medial tibial stress syndrome) (Chuter et al., 2012); therefore understanding how running shoes alter foot mechanics and impacts during running is essential to determining whether runners' injuries are caused by their footwear. Because collision forces and inter-joint coordination are factors that have been described to predispose runners to injury (Wang et al. 2018), Ground reaction force (GRF) measurements would be important for better understanding the mechanisms of action of running shoes, however, unfortunately in this study, we could not acquire GRF because the treadmill was not instrumented and this could be interpreted as a study limitation when comes to understanding footwear mechanism of action in running-related injury.

This study aimed to investigate the association between the rearfoot angle in recreational runners when barefoot and wearing their normal running shoes. Our results refuted two hypotheses and confirmed one: (i) the shoes worn did not correspond to the runners' respective rearfoot motion, since there was no association between the barefoot pattern and type of running shoe (refuted); (ii) using shoes increased the eversion angle in relation to barefoot running (confirmed), (iii) subjective selection of running shoes for a specific rearfoot motion did not correct the eversion angle to within a neutral range (refuted).

The subjective compatibility of the foot arch of runners with running shoes is a determining factor when they select footwear (Enke et al., 2009). An analysis of the association between the type of running shoe, according to the manufacturers' classification (neutral, overpronation, underpronation, motion control and cushion) and rearfoot motion demonstrated that at least 50% of the recreational runners used shoes designed for their barefoot rearfoot motion. In studies that interviewed runners, subjective knowledge of their rearfoot motion was common, with 83.5% of adult runners providing this information (Hespanhol Junior et al., 2012), and 57% of adolescent runners in another investigation reporting they knew their foot arch type (Enke et al., 2009). Thus, our results refuted our initial hypothesis and we concluded that the subjective perception of runners regarding their rearfoot motion and biomechanics during running does not reflect reality.

There was a 4-degree increase in rearfoot eversion when participants wore shoes as opposed to running barefoot. Differences of 2 to 4 degrees between barefoot and shod running have also been reported in other studies (Clarke et al., 1983; Gheluwe et al., 1995; Nigg and Morlok, 1987; Stacoff et al., 1990). Although all these cited studies used different methodologies and protocols to evaluate rearfoot eversion, they have shown similar results regarding the rearfoot eversion range.

Barefoot eversion is up to 8.6 degrees, reaching 16 degrees under shod conditions (Reinschmidt et al., 1997). Unlike our findings and those of other authors (Clarke et al., 1983; Gheluwe et al., 1995; Mei et al., 2015; Nigg and Morlok, 1987; Reinschmidt et al., 1997; Stacoff et al., 1990) reported a higher rearfoot eversion angle in barefoot runners when compared to their shod counterparts. However, RFA differences of up to 20 degrees between barefoot and shod runners are more frequently described in the literature (Stacoff et al., 1990) than no differences or the opposite scenario, as reported by Mei et al., 2015. Thus, our findings confirm the initial hypothesis that running shoes increase the eversion angle in relation to running barefoot.

Analysis of the association between the barefoot rearfoot motion and the effect of shoes on rearfoot motion showed a significant variation in responses caused by footwear. Different mechanical responses on GRF and eversion angle were also observed when different running shoe soles were used (Stacoff et al., 1990; Reinschmidt et al., 1997), and these authors concluded that there is no consistent and homogeneous effect on foot-ankle kinematics when an external element to the body is used. These varying responses and effects led us to believe that running shoes do not cause the intended effect on rearfoot motion for which they are manufactured and that the manufacturers' classification does not correspond to the desired mechanical effect. Analysis of motion control shoes in low arched runners showed no difference in peak heel eversion. Changes were only observed in tibial internal rotation, which may benefit the knee, but does not correct overpronation (Butler et al., 2007).

Since the population of overpronators was small, few inferences could be made about this type of rearfoot motion. Cheung et al. (2007) evaluated the pronation angle before and after muscle fatigue, comparing cushioned and motion control shoes. Running with motion control shoes resulted in smaller pronation and tibial rotation angles than those generated with cushioned shoes both before and after fatigue. Tibial rotation was directly related to the pronation angle (Rose et al., 2011), whereby the lower the rotation the smaller the eversion angle. A decline in the pronation angle was observed in young and mature women wearing motion control shoes, with a more significant effect on the latter (Lilley et al., 2013). As such, motion control shoes seem to prevent excessive pronation angle increases when compared to cushioned footwear. Our results indicated a change in rearfoot motion for all the overpronators in shod running, regardless of the type of shoe chosen.

Selecting running shoes in accordance with the barefoot rearfoot motion had an effect on only 38.9% of neutral runners and 25% of overpronators. Pain levels and training volume increased in female runners who wore motion control shoes over a 13-week training period, and the neutral pronators who wore neutral shoes reported feeling more pain than those who did not (Ryan et al., 2011). Moreover, runners who chose the right shoe for their rearfoot motion did not display a lower risk of injury (Nielsen et al., 2014). Using running shoes for a specific foot arch type also showed no significant effect on rearfoot eversion excursion and peak rearfoot eversion in healthy runners on a prolonged run (Butler et al., 2007). Based on our results, we concluded that specially designed running shoes did not exhibit a correcting effect on rearfoot motion. Furthermore, there is no evidence in the literature that supports the influence of choosing footwear specific to your rearfoot motion on clinical variables such as pain and risk of injury. A recent review (Nigg et al. 2015) proposed two paradigms "preferred movement path" and "comfort filter" related to lower extremity running injuries, rather than running shoes; however, this proposal is still based on inconclusive evidence that would explain exactly the risk factors for a running-related injury.

This study has limitations that should be noted. First, movement was analyzed in two dimensions; however, despite the 2D nature of our analysis, the differences between two and three-dimensional posterior angles are minimal (McClay and Manal, 1998). Another limitation was the use of external markers on the footwear. There is limited research on the influence of running shoes on intersegmental foot kinematics due to the challenges of modelling the feet inside shoes (Reinschmidt et al., 1997), however, Bishop et al. (2013) presented minimal (<6,7mm) difference in set markers applied on the shoe and over the foot skin. Furthermore, rearfoot motion has been measured by different studies using exactly the same methodology used in this study for decades until today (Cheung et al., 2007; 2010; Kernozek et al., 1990; Kong et al., 2011; Kosonen et al., 2017; McClay and Manal, 1998; Morley et al., 2010). The third limitation is that the study was conducted on a treadmill, which could restrict generalization of the results for overground running; however, a recent systematic review (Miller et al., 2019) showed that motorized track running kinematics is broadly comparable to ground running kinematics.

Conclusion

The footwear worn by the runners did not correspond to their respective barefoot rearfoot motion, since there was no association between these patterns and the shoes used, which led us to conclude that they did not choose shoes designed for their type of rearfoot motion. The eversion angle increased during running with shoes compared to barefoot condition, meaning that rearfoot kinematics is changed in shod running. Finally, wearing running shoes designed for their rearfoot motion did not correct the pronation of this population to within a normal range, as claimed by the manufacturers.

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Key points

- The footwear worn by the runners did not correspond to their respective barefoot rearfoot motion.
- The eversion angle is greater during running with shoes than barefoot condition, meaning rearfoot kinematics is changed in shod running.
- Wearing running shoes designed for their rearfoot motion did not correct the pronation.

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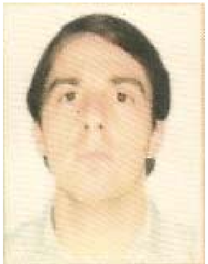

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