TITLE PAGE

Title

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

Running Title

Effect of minimalist shoes on running kinematics

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KEYWORDS

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

ABSTRACT

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

KEYWORDS

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

1. INTRODUCTION

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

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

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

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

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

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

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

2. METHODS

2.1 Design

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

2.2 Participants

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

2.3 Data collection and processing

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

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

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

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

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

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

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

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

---INSERT FIGURE 1 ABOUT HERE---

2.4 Statistical analysis

Statistical analysis was carried out with SPSS® software (IBM®, New York, USA). Average measures from individual participants were used to characterise each shoe condition through descriptive statistics. A one-way repeated-measures ANOVA was used to determine the effects of shoe-types on running parameters. Effect sizes were assessed by calculating eta-square (η^2). Where appropriate, a Tukey's test was used in the post-hoc analysis to assess differences between conditions. Significance was accepted at $p<0.05$ level. For significant post hoc findings the percentage mean difference, 95% CIs and standardised mean difference (SMD) were also calculated.

3. RESULTS

Among the footwear models, laboratory tests demonstrated wide variations in mass (range: 127-330 g), stack height at the heel (range: 7-28 mm) and forefoot (range: 7-42 mm), heel-toe drop (range: 0-14mm), shock-absorption (range: 9-19 m/s2) and flexibility (range: 0.2-5.9 N•m) (Table 1).

---INSERT TABLE 1 ABOUT HERE---

The strike index (Table 2) indicated that all the subjects used a rearfoot strike pattern in the cushioned shoe and did not change to a full midfoot or forefoot contact while running in minimalist footwear and barefoot. However, for this variable, there was a significant main effect for foot condition ($F(7,91)=12.74$, $p<0.001$, $\eta^2=0.55$), with the participants that shifted anteriorly to 45% (~2.3 cm; CI 30% to 60%, $p<0.05$, SMD=1.6) of the initial point of contact with the ground when progressing from the cushioned model to barefoot. The post-hoc analysis indicated that the minimalist footwear can be divided into two groups: (1), Saucony, Nike and Newton Running shoe; and (2) Inov8, New Balance and Vibram Fivefingers shoe, with a more anterior foot strike (average mean difference ~30%, ~1.6 cm) going from the models of the group 1 to those of group 2.

These changes in foot strike pattern were confirmed by foot contact angle. A main effect for foot condition ($F(7,91)=6.38$, $p<0.001$, $\eta^2=0.43$) was found for this variable, with shoes of group 2 characterized by a significant flatter (i.e. less dorsiflexed) foot position (~35%) at ground contact compared to those of group 1 (Table 2).

---INSERT TABLE 2 ABOUT HERE---

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

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

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

Knee contact angle ($F(7,91)=4.07$, $p<0.001$, $\eta^2=0.40$), knee ROM ($F(7,91)=5,41$, $p<0.001$, $\eta^2=0.42$), and hip vertical displacement ($F(7,91)=5.72$, $p<0.001$, $\eta^2=0.42$) showed main effects for running conditions, whereas stride angle, overstride angle and peak knee flexion appeared invariant to the type of footwear (Table 2).

In the cushioned shoe and in the Nike shoe, knee angle at heel strike was significantly more extended than in barefoot (1,7%, CI 0.7% to 2.7%; $p=0.000$, SMD=0.9, and 1,5%, CI 0.5% to 2.5%, $p=0.007$, SMD=0.8, respectively). Comparing the minimalist models, the knee was 1.1% (CI 0.2% to 2%, $p=0.034$, SMD=0.6) more flexed when running in Inov8 than in Nike shoe. Knee ROM was lower in barefoot and higher in cushioned model, with Inov8, Vibram Fivefingers and New Balance shoe characterised by values significantly lower than in cushioned shoe (8.6%, *p*=0.01, SMD=0.6, 9%, *p*=0.02, SMD=0.6 and 7.8%, *p*=0.02, SMD=0.56, respectively) and by a non-significant trend of higher values compared to barefoot. The Nike and Saucony shoes had increased vertical hip displacement than the barefoot condition and all the other minimalist models.

4. DISCUSSION

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

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

These results confirm and extend what was found by prior studies on minimalist footwear and help to explain the apparent inconsistency of some of them which came to different conclusions regarding the efficacy of minimalist shoes. Specifically, our findings on Nike Free model agree with Willy and Davis (2013) who concluded that running in this shoe failed to result in changes in spatio-temporal parameters when compared with running in a standard running shoe. The results also agree with Bonacci et al. (2013) and Sinclair et al. (2013), who concluded that the mechanics of this footwear does not appear to closely mimic the kinematics of barefoot locomotion in experienced runners. In addition, our findings on the Vibram Fivefingers shoe confirm, even for rearfoot strikers, the findings of Squadrone & Gallozzi (2009), that found that this type of shoes have no significant effect on barefoot running kinematics.

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

With minimalist footwear, the strike index values were between the cushioned shoe (closer to the heel) and the barefoot condition (closer to a midfoot strike) with some footwear (e.g. Group 1 - Newton Running, Saucony, Nike shoe) closer to a definitive rearfoot strike and others (e.g. Group 2 - New Balance, Inov8, Vibram Fivefingers shoe) closer to a midfoot strike. These differences can be explained in terms of the construction of the two groups of minimalist footwear. Group 1 shoes had a greater heel stack height (22 to 26 mm) than those of Group 2 (7 to 13 mm). Similar to the reasoning for the difference in the cushioned shoe and the barefoot condition, the greater heel height resulted in more material to protect the heel on impact in Group 1 shoes, whereas there was insufficient heel material in Group 2 shoes to prevent the possible heel pain at foot contact. The result is a more forward (i.e. closer to midfoot) contact in Group 2 shoes. This interpretation is reinforced by the results of shock absorption tests were the shoes of Group1 showed shock absorption characteristics better than those of Group 2 and similar to the cushioned shoe.

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

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

The results from our study are in line with those previously found by Divert et al. (2005) and Squadrone & Gallozzi (2009) in sub-elite athletes running on a treadmill at the same speed, and by Bonacci et al. (2013) in highly trained runners. The runners analysed by those authors, progressively adopted shorter stride lengths and higher stride frequencies when running condition changes from cushioned to minimalist and from minimalist to barefoot. Reduced stride length has been shown to decrease impact characteristics and to increase shock attenuation (Derrick, Hamill, & Caldwell, 1998; Mercer, Vance, Hreljac, & Hamill, 2002). Therefore, once again, the attempt to reduce the possible pain caused by the heel-ground contact while barefoot or in minimalist footwear would suggest these alterations.

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

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

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

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

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

5. CONCLUSION

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

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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/s2)	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.

	Barefoot	Vibram Fivefingers Seeya	Inov8 Bare-X 200	New Balance MR00GB	Newton Running MV2	Saucony Kinvara 2	Nike Free 3.0V4	**Cushioned shoe**
Foot strike variables								
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 *
Spatio-temporal stride variables								
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±0.04	2.34±0.04*# *a*	2.38±0.05* *b*	2.37±0.04* *b*	2.35±0.05* *a*	2.37±0.04* *b*	2.38±0.05* *b*	2.38±0.05*
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*
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*
Kinematic variables								
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±3.2 a,b	164.5±3 # a	165.2±3.3 a,b	165.4±3.3 a,b	165.6±3.2 a,b	166.3±3.1*b	166.6±3.2*
Peak stance knee flex angle (°)	138.8±4.6	138.5±4.3	137.9±4.5	138.2±4.7	138.0±4.6	137.6±4.4	137.4±4.2	137.5±4.2
Knee ROM stance phase (°)	25.1±4.2	26.7±4.2 #*a*	26.6±4.1 #*a*	26.9±3.8 #*a*	27.4±4.0 **a*	28.0±4.1**a,b*	28.9±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).