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Research article

Lower Extremity Biomechanical Relationships with Different Speeds in Traditional, Minimalist, and Barefoot Footwear

William Fredericks [1,3], Seth Swank [2], Madeline Teisberg [3], Bethany Hampton [3], Lance Ridpath [3] and Jandy B. Hanna [3]✉

[1] Mayo Clinic & WVSOM, Rochester, MN, USA; [2] University of Michigan Health System, Ann Arbor, MI, USA, [3] WVSOM, Lewisburg, WV, USA

Abstract

Minimalist running footwear has grown increasingly popular. Prior studies that have compared lower extremity biomechanics in minimalist running to traditional running conditions are largely limited to a single running velocity. This study compares the effects of running at various speeds on foot strike pattern, stride length, knee angles and ankle angles in traditional, barefoot, and minimalist running conditions. Twenty-six recreational runners (19-46 years of age) ran on a treadmill at a range of speeds (2.5-4.0 m·sec^{-1}). Subjects ran with four different footwear conditions: personal, standard, and minimalist shoes and barefoot. 3D coordinates from video data were collected. The relationships between speed, knee and ankle angles at foot strike and toe-off, relative step length, and footwear conditions were evaluated by ANCOVA, with speed as the co-variate. Distribution of non-rearfoot strike was compared across shod conditions with paired t-tests. Non-rearfoot strike distribution was not significantly affected by speed, but was different between shod conditions ($p < 0.05$). Footwear condition and speed significantly affected ankle angle at touchdown, independent of one another ($F [3,71] = 10.28$, $p < 0.001$), with barefoot and minimalist running exhibiting greater plantarflexion at foot strike. When controlling for foot strike style, barefoot and minimalist runners exhibited greater plantarflexion than other conditions ($p < 0.05$). Ankle angle at lift-off and relative step length exhibited a significant interaction between speed and shod condition. Knee angles had a significant relationship with speed, but not with footwear. There is a clear influence of footwear, but not speed, on foot strike pattern. Additionally, speed and footwear predict ankle angles (greater plantarflexion at foot strike) and may have implications for minimalist runners and their risk of injury. Long-term studies utilizing various speeds and habituation times are needed.

Key words: Running, biomechanics, gait analysis, motion analysis/kinesiology, minimalist, shoe wear.

Introduction

The incidence of lower extremity injury in traditional running shoes (TRS) is as high as 79.3% (van Gent et al., 2007). Of these injuries, the knee and ankle are the most commonly injured (van Gent et al., 2007). Such injuries include patellofemoral pain syndrome (Clement et al., 1981; Taunton et al., 2002; Tiberio, 1987), Achilles tendinopathy (Clement et al., 1981; Smart et al., 1980; Taunton et al., 2002), and medial tibial stress syndrome (Clement et al., 1981; Taunton et al., 2002; Vtasalo and Kvist, 1983). In an effort to avert the injuries associated with TRS, many people have adopted the use of minimalist running shoes (MRS). MRS arguably simulate barefoot running by replicating barefoot biomechanics (Goss and Gross, 2012; Robbins and Hanna, 1987; Vormittag et al., 2009). Some studies, however, suggest that MRS still cause injuries, just different ones from those caused by TRS (Goss and Gross, 2012; Guiliani et al., 2011). Thus, the data are equivocal on whether MRS decreases injury risk or are "better" than TRS. Short of prospective studies examining injury rates between different shoes (Lieberman et al., 2010), one approach to this question is to identify biomechanical factors contributing to injury risk in order to avoid injury altogether.

The effect of footwear on biomechanics and injury rates/types is complicated by at least two factors. First, foot strike pattern may be related to injury incidence (Daoud et al., 2012; Goss and Gross, 2012) and foot strike may change with footwear (Bonacci et al., 2013; Lieberman et al., 2010; but see McCallion et al., 2014). If MRS cause increased forefoot strike, the increased plantarflexion would result in reduced instability of the ankle mortise (Wright et al., 2000), and predispose MRS runners to ankle sprain. Second, speed is another factor complicating comparisons between TRS and MRS (Goss and Gross, 2012; Lieberman et al., 2010). Increasing speed in TRS causes greater midfoot and forefoot strikes (Keller et al., 1996), but whether this same relationship is true when running in MRS or barefoot is untested. One recent MRS study has collected data at two categories of speed (e.g. fast and slow) (McCallion et al., 2014), but others have constrained analyses to a single speed (e.g. Cheung and Rainbow, 2014; Divert et al., 2008; Shih et al., 2013; Sinclair, 2014; Sinclair et al., 2013). Thus, how foot strike changes *as speed increases* is not well understood (Tam et al., 2014).

Speed affects knee and ankle biomechanics in traditional shoes (Arampatzis et al. 1999; Bishop et al. 2006; Lohman III et al. 2011). Prior works on kinematic differences between running footwear have been conducted at single speeds and the results vary depending on the speed utilized. For example, at 4.0 m·sec^{-1}, knee angles are not affected by footwear, whereas ankle angles are affected (Sinclair et al., 2013). In contrast, at 4.48 m·sec^{-1}, knee angles are affected by footwear (Bonacci et al., 2013). Foot strike style also may be implicated in such differences (Perl et al., 2012). Therefore, the relationships between knee and ankle joint kinematics and speed, foot strike style and speed in various footwear conditions, and

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the interaction between speed and footwear, deserve further investigation.

This study investigates the effects of speed on running biomechanics, foot strike and step length with various footwear conditions through several questions. 1) Does increasing speed affect foot strike pattern, lower limb joint kinematics, or relative step length? 2) Does changing footwear, but not footwear type, affect foot strike pattern, lower limb joint kinematics, or relative step length? 3) Does changing footwear type affect foot strike pattern, lower limb joint kinematics, or relative step length? 4) Do kinematics or relative step length differ among shod conditions *within* a foot strike style?

Methods

Participants

Twenty six recreational runners were recruited and completed this study. Recreational runners were the target group so the results will be applicable to the general population, rather than trained/elite athletes. In this way, the results are more clinically relevant to family practice physicians who may be asked to advise patients regarding running shoes. Recreational runners are defined as in Gehring et al. (1997), where recreational runners are those who train at a speed of slower than 3.33 m·sec^{-1} and run at between 24 and 40 km·week^{-1}. Thirteen subjects were male and thirteen were female. Subjects were healthy individuals who ran at least 30 minutes twice weekly and were naïve to barefoot or minimalist running. Each subject completed a survey estimating average running speed and distance per week (Table 1). Typical running surface was recorded as either hard (concrete, sidewalk), medium (asphalt, road, track, treadmill), or soft (grass, gravel, trail). Finally, personal running shoe brand was recorded.

Table 1. Summary subject data (n = 26). Data are means (±SD) [min-max].

Age (yrs)	**26.5 (6.1) [19.0-46.0]**
BMI	**22.7 (2.8) [19.1-28.9]**
Weight (kg)	**66.6 (11.3) [52.2-98.8]**
Height (m)	**1.71 (.10 [1.53-1.90]**
Leg length (m)	**.43 (.04) [.36-.49]**
Running speed (m·sec^{-1})	**3.09 (.62) [1.79-4.69]**
Distance per week (km)	**25.8 (20.7) [5.2-92.5]**

Instrumentation

Kinematic data were collected during running on a Cybex© 770T-CT treadmill (Cybex International, Inc.; Medway, MA). Five reflective markers were placed on the left lower limb: 1) 3 cm proximal to the lateral femoral epicondyle,(*It is typical to define the thigh segment using the greater trochanter, however, this landmark was often obscured by the treadmill in our study. Thus, we created a point along the line created by the greater trochanter and the lateral femoral epicondyle. This point was created to ensure the marker would not be obscured by the subjects' chosen clothing or the arm of the treadmill.*) 2) the lateral femoral epicondyle, 3) the lateral malleolus, 4) the calcaneal tuberosity (or the appropriate point on the shoe), and 5) the fifth metatarsal head (Figure 1). Data collection and analysis of the left limb, only, ensured independence of data for each stride. Video data were collected at 100 Hz using two digital video cameras (Basler A601f®; Basler AG, Ahrensburg, Germany), 70 degrees from each other, placed lateral to the treadmill. Digital cameras interfaced with a personal computer using Streampix® software (NorPix, Inc.; Montreal, Quebec, Canada). Video data were synchronized with an Innovision Systems, Inc. setup (Columbiaville, MI). The cameras were calibrated using a static, calibrated 8-point calibration cube (Hedrick 2008). Lower extremity reflectors provided data for video digitizing, kinematic analysis, and spatiotemporal calculations, completed with MaxTraq3D® and MaxMate® systems (Innovision systems, Inc.; Columbiaville, MI).

Procedures

Prior to subject participation, the study was described to each subject along with potential risks and benefits of participation, after which informed consent was obtained as approved by the WVSOM Institutional Review Board, in accordance with the Belmont report. Subject age, height, body mass, and leg length, measured with calipers (Paleo-Tech linear spreading calipers; Paleo-Tech Concepts, Crystal Lake, IL), were recorded at the initial visit. The subject then completed the survey described above.

Shod conditions: Data were collected for a single, different footwear condition at each visit. Visits were on consecutive days to avoid fatigue. Footwear conditions included: 1) personal traditional running shoe (personal), 2) standardized traditional running shoe (Nike© Air Pegasus+ 27; Nike, Inc., Beaverton, OR) (standard) to determine if results were due to changing footwear, 3) minimalist shoe (Ryan et al. 2014) (Vibram FiveFinger© KSO; Concord, MA) (minimalist), and 4) barefoot without shoe (barefoot). The initial visit was always in the personal shoe and the remaining shod condition visits were randomized to minimize effect of order. While there are a variety of choices for minimalist shoes, this particular model (Vibram FiveFinger©; Concord, MA) is arguably one of the closest to barefoot running. The KSO has a maximum sole thickness of < 5mm, while other minimalist/hybrid shoes have a thicker sole, particularly at the heel (5mm <heel lift < 10mm). Utilizing this style of minimalist shoe should ensure that differences between it and barefoot running are due to wearing *any* footwear, while differences between the minimalist shoes and conventional shoes are due to the fact that the sole is minimized.

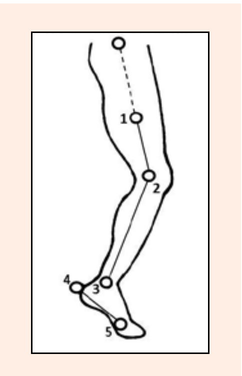

Figure 1. Representation of the marker set used for data collection. Marker set and angle calculation are based on Winter, 2005. The unlabeled marker is the greater trochanter. The numbered markers are as described in the text.

Table 2. Post-hoc t-tests (one-way ANOVA) of mean forefoot strike distribution (across all speeds) between shod conditions.

Shod condition	Comparison	Mean (±SE) of forefoot distribution for all speeds	Estimate	SE	Z-Statistic	p-Value
Barefoot		.47 (.015)				
	Barefoot vs. Personal		-.55	.24	-2.31	.02
	Barefoot vs. Standard		-1.06	.40	-2.63	.01
	Barefoot vs. Minimalist		.10	.18	.53	.60
Personal		.26 (.011)				
	Personal vs. Standard		-.52	.34	-1.50	.13
	Personal vs. Minimalist		.64	.25	2.63	.01
Standard		.20 (.011)				
	Standard vs. Minimalist		1.16	.42	2.78	.01
Minimalist		.48 (.014)				

SE: Standard Error

Data collection: At each visit, subjects ran on the treadmill at four speeds over 18-27 minutes. Initial speed was 2.5 m sec^{-1} and increased sequentially every three minutes to 3.0, 3.5, 4.0 m·sec^{-1}. Approximately fifteen seconds of video were collected at each speed, to capture 10 strides at each speed for analysis. Speeds encompass recreational running speeds and encompass those examined in previous work (e.g. 2.2 m·sec^{-1} to 4.0 m·sec^{-1}: Goss and Gross 2012; Kong et al. 2009; Queen et al. 2006; Reinking et al. 2013).

Limb segments were defined as follows: 1) Thigh-from the mid-thigh to lateral epicondyle of the femur, 2) Leg-from the lateral epicondyle of the femur to the lateral malleolus, 3) Foot-from the calcaneus to 5^{th} metatarsal. Using these segments, the knee angle was defined by the thigh and leg segments, as in Winter (2005). The ankle angle was defined by the leg and foot segments (Figure 1), as described in Winter (2005), but calculated with negative being plantarflexion and dorsiflexion as positive. Angles were calculated at initial foot strike and foot lift-off, or toe-off. Step length (distance traveled by 5^{th} metatarsal from foot strike to toe-off), duration of ground contact, and foot strike pattern were also recorded.

Ground contact and toe-off were determined from visual inspection and confirmed utilizing the method described by De Witt (2010). Visual determination of ground contact has limited error (up to 1.5 frames) (Ghoussayni et al. 2004). Rearfoot strike pattern was determined visually as first ground contact of the foot being at the posterior 1/3 (Cheung and Rainbow 2014). The number of non-rearfoot strikes (Cheung and Rainbow 2014) (termed non-rearfoot strike in this study) was divided by the total number of trials for each subject in order to calculate the ratio of non-rearfoot strike. Digitized three-dimensional coordinates were interpolated and filtered using a Butterworth low pass filter, with a cut-off frequency of 8 Hz (Winter, 2005).

Statistical analysis

Repeated-measures analysis of covariance (ANCOVA) was calculated for kinematic or spatiotemporal variables (i.e. non-rearfoot strike distribution, knee angle, ankle angle, step length) during running (dependent variable) with speed (co-variate) in different footwear conditions. Knee angle at foot strike and toe-off, ankle angle at foot strike and toe-off, and relative stride length were examined using ANCOVA. Post-hoc paired t-tests were calculated if there was no significant relationship with speed. Finally, the relationship within a foot strike type (i.e. rearfoot or non-rearfoot) between footwear condition and ankle angle at foot strike was assessed using paired post-hoc ANOVAs. All data were analyzed using SPSS for Windows Version 20.0 (Chicago, IL) at a significance level of $p \le 0.05$.

Results

Average self-reported running speed was 3.09m sec^{-1} (SD = 0.62 m·sec^{-1}) (Table 1). Typical running surface grade was hard for 7.50%, medium for 65.0% and soft for 25.5% of subjects. The most commonly used running shoe brand was Asics (34.6%).

Speed

ANCOVA results reveal that foot strike distribution is not significantly related to speed across shod conditions. Post-hoc comparison of foot strike distribution reveals mean non-rearfoot strike distributions with barefoot and MRS do not differ, and the same is true between personal and standard shoes (Table 2). Mean non-rearfoot strike distribution during barefoot or MRS is significantly higher than the mean in either TRS.

Ankle kinematics across all foot strike types

Speed predicted ankle angle at foot strike ($F [3,46] = 6.87$, $p < 0.001$) for all footwear conditions, indicating that plantarflexion increased with speed. Footwear also predicted ankle angle at foot strike ($F [3,71] = 10.28$, $p < 0.0001$) (Figure 2). Post-hoc pairwise comparisons revealed that barefoot and MRS did not differ ($t = 0.93$, $p = 0.3571$), nor did either TRS ($t = 0.65$, $p = 0.5183$). Barefoot and MRS ankle foot strike angles differed from both TRS ($t = 3.03$ to 4.65, $p = 0.0034$-0.0001). There was no interaction between speed and shod condition of ankle plantarflexion at foot strike, but there was an interaction effect of speed and shod condition for toe-off plantarflexion (Figure 2).

Ankle kinematics in rearfoot strikes

Plantarflexion in rearfoot strike was greater for barefoot versus both TRS, while MRS differed only from standard condition (Table 3). Toe-off plantarflexion in rearfoot strikers was greater when barefoot versus minimalist ($t = 2.28$, $p = 0.04$, $n = 26$), standard ($t = 3.69$, $p < 0.01$, n =

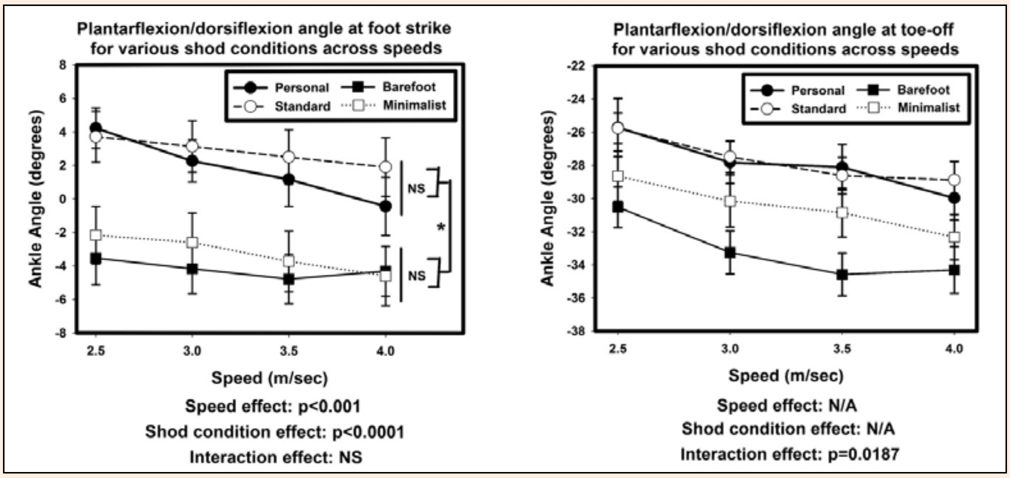

Figure 2. Foot strike and toe-off plantarflexion angles, analyzed by shod condition as speed increases. Sample number for each symbol is 26. Bars indicate standard error. NS indicates no significant difference between the shod conditions overlapped by the vertical line. * indicates a statistical difference between shod conditions overlapped by the line. See text for statistical discussion.

26), and personal shoes ($t = 2.78$, $p = 0.01$, $n = 26$). Toe-off plantarflexion in rearfoot strikers was greater in minimalist versus standard footwear ($t = 2.14$, $p = 0.05$, $n = 26$) (Table 3). Toe-off plantarflexion in rearfoot strikers was greater in personal footwear versus barefoot ($t=2.80$, $p=0.03$, $n=26$) and minimalist footwear ($t = 2.45$, $p = 0.05$, $n = 26$) (Table 3).

Ankle kinematics in non-rearfoot strikes

Non-rearfoot strike plantarflexion was greater in barefoot than MRS ($p = 0.05$), both of which were greater than either TRS (various $p < 0.05$). Toe-off plantarflexion in non-rearfoot striking was greater in minimalist and barefoot conditions than personal condition (various $p < 0.05$) (Table 4).

Knee kinematics across all foot strike types

Speed predicted knee angle at foot strike ($F\ [3,43] = 15.62$, $p < 0.001$) and knee angle at toe-off ($F\ [3,45] = 32.97$, $p < 0.001$) for all footwear conditions. Faster speeds resulted in greater knee flexion at foot strike and greater knee extension at toe-off (Figure 3). Footwear did not affect foot strike knee angle or toe-off knee angle ($p > 0.05$). There was no interaction between speed and footwear on knee flexion during foot strike or toe-off.

Relative step length across all foot strike types

Speed and footwear predicted relative step length ($F\ [11,9] = 2.45$, $p = 0.01$). Relative step length was larger in standard versus minimalist footwear ($t = 5.69$, $p < 0.01$, $n = 26$), personal footwear ($t = 3.39$, $p < 0.01$, $n = 26$), and barefoot conditions ($t = 5.69$, $p < 0.01$, $n = 26$). Relative step length was larger in personal versus both minimalist footwear ($t = 3.39$, $p < 0.01$, $n = 26$) and barefoot conditions ($t = 3.39$, $p < 0.01$, $n = 26$) (Figure 4). There was, however, an interaction effect between speed and shod condition in terms of relative step length.

Discussion

Increasing speed does not affect foot strike pattern, whereas changing shod condition from TRS to MRS and

Table 3. Analysis within just rearfoot strikes. Paired t-test between footwear types of ankle angles (in degrees) and relative step length within one foot strike styles.

Plantarflexion angle at foot strike (SD)	Mean/Mean	T P<	Plantarflexion angle at toe-off (SD)	Mean/Mean	T P<	Relative step length Mean/Mean (SD)	T P<
Barefoot>Standard N = 19 (7.63)	-1.08/5.41	3.71 **.00**	Barefoot>Minimalist N = 18 (4.74)	-33.53/-30.98	2.28 **.04**	Standard>Barefoot N = 19 2.11/2.00 (.09)	5.69 **.000**
Minimalist>Standard N = 18 (9.94)	-.31/5.79	2.60 **.02**	Barefoot>Standard N = 19 (6.39)	-33.63/-28.21	3.69 **.00**	Standard>Minimalist N = 18 2.12/1.98 (.16)	3.88 **.000**
Barefoot>Personal N = 19 (6.84)	-1.08/3.21	2.73 **.01**	Minimalist>Standard N = 18 (6.38)	-30.98/-27.77	2.14 **.05**	Personal>Barefoot N = 19 2.07/2.00 (.09)	3.45 **.000**
			Barefoot>Personal N = 19 (6.86)	-33.63/-29.25	2.78 **.01**	Personal>Minimalist N = 18 2.08/1.98 (.13)	3.30 **.000**
						Standard>Personal N = 22 2.09/2.05 (.06)	3.39 **.000**

SD: Standard Deviation of Differences. N is the number of subjects that exhibited the foot strike type in both conditions being analyzed. A summary of the pattern of degree of plantarflexion across footwear is provided at the bottom of each set of comparisons.

Table 4. Analysis within just non-rearfoot strikes. Paired t-test between footwear types of ankle angles (in degrees) and relative step length within one foot strike styles.

Plantarflexion angle at foot strike (SD)	Mean/Mean	T P<	Plantarflexion angle at toe-off (SD)	Mean/Mean	T P<
Barefoot>Minimalist N = 9 (4.31)	-11.55/-8.18	2.34 **.05**	Barefoot>Personal N = 7 (7.34)	-32.77/-24.99	2.80 **.03**
Minimalist>Personal N = 7 (2.91)	-9.98/-4.40	4.98 **.00**	Minimalist>Personal N = 7 (6.19)	-32.14/-26.40	2.45 **.05**
Barefoot>Personal N = 7 (5.20)	-11.18/-3.75	3.78 **.01**			
Barefoot>Standard N = 3 (2.74)	-17.25/-9.92	4.63 **.04**			

SD: Standard Deviation of Differences. N is the number of subjects that exhibited the foot strike type in both conditions being analyzed. A summary of the pattern of degree of plantarflexion across footwear is provided at the bottom of each set of comparisons.

barefoot increases the frequency of non-rearfoot strike. For runners who do not change foot strike style, changing shod condition from TRS to MRS or barefoot is associated with increased ankle plantarflexion at foot strike. Increasing speed causes increased ankle plantarflexion and increased knee flexion. Runners who switch to MRS and continue to heel strike will lose the benefit of lower rates of loading through the joints (Lieberman et al., 2010) and also lose the cushioning provided by TRS. At faster speeds, such problems may be compounded as speed typically is associated with higher forces.

Speed

Previous studies have examined the effects of shod condition at a single, and relatively high, speed (e.g. Lieberman et al., 2010: >4.0 m·sec^{-1}; Sinclair, 2014; Sinclair et al., 2013: 4.0 m·sec^{-1}). Survey results indicate that recreational runners do not tend to utilize speeds that high. Such previous work may have limited application to the general runner population. In our study, recreational speeds significantly influenced joint angles in all footwear conditions. Changes in joint angles affect joint moments and stiffness in TRS (Arampatzis et al., 1999; Günther and Blickhan, 2002; Kerrigan et al., 2009), which suggests increased injury risk (Hamill et al. 2012). Runners at risk for knee and ankle overuse injuries may wish to run at reduced speeds if switching to MRS to minimize kinetic changes and thus injury risk.

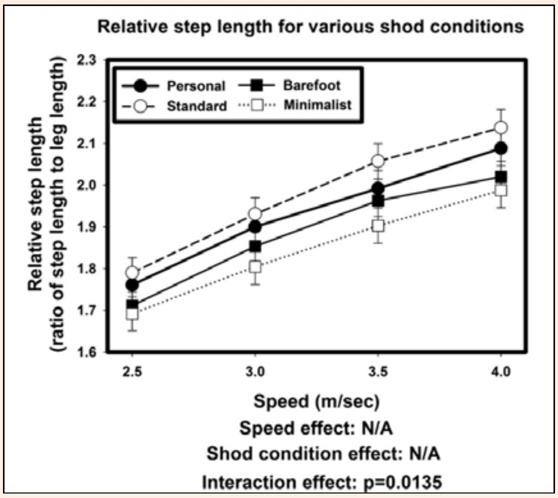

Figure 4. Relative step length analyzed by shod condition as speed increases. Sample number for each symbol is 26. Bars indicate standard error. There is a significant interaction between speed and shod condition, such that as speed increases, relative step length increases faster in personal and standard shoes than in minimalist or barefoot conditions. See text for statistical discussion.

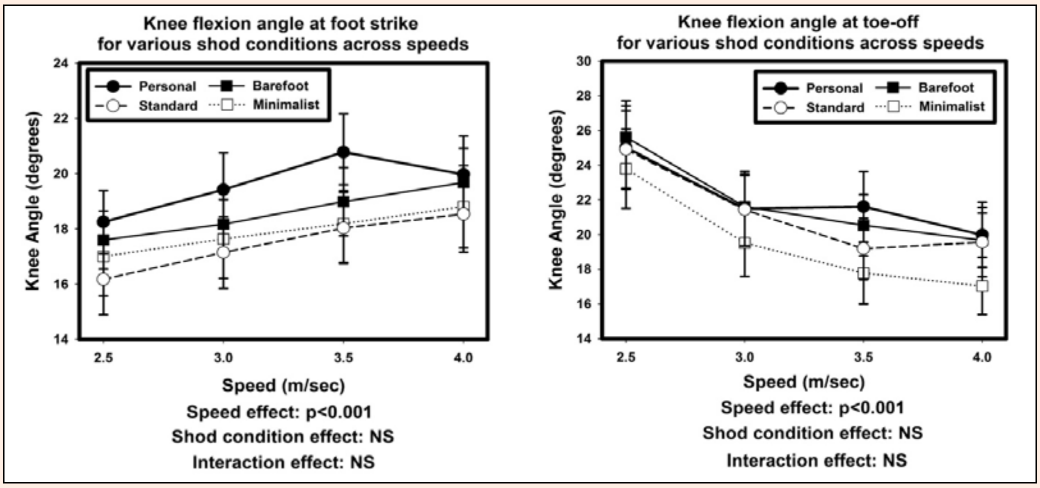

Figure 3. Foot strike and toe-off knee flexion angles, analyzed by shod condition as speed increases. Sample number for each symbol is 26. Bars indicate standard error. There is no significant difference (NS) between the shod conditions. There is a significant effect of speed on knee flexion angles. See text for statistical discussion.

Foot strike pattern

Foot strike differed between TRS and MRS, but did not change with speed. Hatala and colleagues (2013) illustrated a similar relationship between foot strike and speed in barefoot runners, while the same is true for runners in TRS until higher speeds are reached (Keller et al., 1996). If changing foot strike style is representative of a body self-selecting for injury reducing behavior, our results support the findings of Hatala (2013), in that recreational runners who change shod condition may not be at as high a risk for injury as those who train at faster and more frequent intensities. The similarity in foot strike between MRS and barefoot is consistent with earlier studies suggesting MRS biomechanics resemble those of running barefoot (Squadrone and Gallozzi, 2009). This influence of footwear on foot strike pattern and ankle angle corroborates previous work (Goss and Gross, 2012; Lieberman et al. 2010), but contrasts a recent study (McCallion et al., 2014). The greater incidence of non-rearfoot strike with MRS may function to reduce impact forces without shoe cushioning (Lieberman et al., 2010). However, this increased plantarflexion may predispose runners to ankle injuries, as ankle mortise becomes less stable and the risk of both ankle fracture and ankle sprain increases (Wright et al., 2000).

Within foot strike styles, plantarflexion is increased in MRS and barefoot compared to TRS. While footwear affects foot strike pattern, footwear *independently* affects ankle angle, regardless of strike type. These results suggest an optimal foot strike and toe-off angle, regardless of foot strike style, when utilizing MRS versus TRS. This finding reinforces the importance of shod condition (contra Shih et al., 2013).

Joint ankles

Results indicate that footwear does not affect knee angles. This contrasts a previous report that MRS exhibit increased knee flexion compared to TRS (Shih et al., 2013). This discrepancy may relate to changes occurring to knee angles more gradually than ankle angles, as footwear influences biomechanical changes over time (Hamill et al., 2012; TenBroek, 2011). Alternative explanations are that knee moments are decreased in MRS, despite no difference in knee angles between shod conditions (Sinclair, 2014), or limb compliance and its force effects (Ferris et al., 1999; Ferris et al., 1998; Geyer et al., 2006).

Step length

The decrease in relative step length in MRS corroborates previous reports (Bonacci et al., 2013; Franz et al., 2012; Kerrigan et al., 2009; Squadrone and Gallozzi, 2009). Here, however, an interaction effect between speed and shod condition indicates that step length increases more rapidly with speed in TRS than in MRS or barefoot. This interaction may illustrate a compensatory mechanism for running in MRS or barefoot, as reduced stride length allows for reduction in ground reaction forces (Korhonen et al., 2009).

Limitations

This study is not without limitations. Treadmill running engenders lower stresses and postural adaptations (e.g. Baur et al., 2007; Milgrom et al., 2003; Nigg et al., 1995) and may not compare to running outdoors. Although broadening these results to overground running should be done with caution (Wall and Charteris, 1980), the general patterns will be similar (e.g. increasing speed causes increased ankle plantarflexion), although the absolute relationships may not compare (Sinclair et al., 2013).

An additional limitation is that subjects were not habituated to MRS or barefoot running. Previous reports show that habituation to a shod condition or specific substrate may affect the biomechanics and energetics of running (e.g. Divert et al., 2005; Schieb, 1986; Wall and Charteris, 1980; Wall and Charteris, 1981; Warne et al., 2013; Warne and Warrington, 2014). Similarly, the change from a rearfoot strike pattern to a non-rearfoot strike pattern may require habituation (Hamill et al., 2012). Thus, results should be interpreted with caution since the subjects in this study were naïve barefoot and minimalist runners. Future investigations should longitudinally compare incidence of knee versus ankle injuries in MRS. Additionally, measuring ground reaction forces in different footwear as speed increases would provide further insight into how impact forces influence running biomechanics.

Conclusion

Our study reveals that foot strike pattern changes with footwear, but not with speed. However, footwear condition and speed affect ankle kinematics, whereas just speed affects knee kinematics. Speed should be considered when switching to MRS, and strategies for minimizing injury risk should be considered. Further studies are needed to determine how speed affects injury risk and what the appropriate transition period is for switching footwear.

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Key points

- Foot strike style does not change with speed, but does change with shod condition, with minimalist shoes exhibiting an intermediate distribution of forefoot strikes between barefoot and traditional shoes.
- Plantarflexion at touchdown does change with speed and with shoe type, with barefoot and minimalist shoes exhibiting a greater plantarflexion angle than traditional running shoes.
- Knee angles change with speed in all shod conditions, but knee flexion at touchdown is not different between shod conditions.
- Relative step length changes with speed and shod condition, but there is an interaction between these variables such that step length increases more quickly in traditional shoes as speed increases.

AUTHORS BIOGRAPHY

William FREDERICKS
Employment
A Physical Medicine and Rehabilitation residency at the Mayo Clinic in Minnesota.
Degree
MD
Research interest
Sports medicine and rehabilitation
E-mail: wfredericks@osteo.wvsom.edu

Seth SWANK
Employment
A Physical Medicine and Rehabilitation residency in Ann Arbor Michigan.
Degree
MD
Research interest
Sports medicine and rehabilitation
E-mail: sswank@umed.mich.edu

Madeline TEISBERG
Employment
An intern in psychiatry at Walter Reed National Military Medical Center.
Degree
MD
Research interest
Sports medicine and rehabilitation
E-mail: mteisberg@osteo.wvsom.edu

Bethany HAMPTON
Employment
A research assistant at West Virginia School of Osteopathic Medicine
Degree
BSc
Research interest
Human locomotion
E-mail: bhampton@osteo.wvsom.edu

Lance RIDPATH
Employment
Coordinator of Institutional Research" in the department of Assessment and Development at West Virginia School of Osteopathic Medicine
Degree
MSc
Research interest
Curricular assessment and quality improvement
E-mail: lridpath@osteo.wvsom.edu

Jandy B. HANNA
Employment
Associate Professor at West Virginia School of Osteopathic Medicine
Degree
PhD
Research interest
Primate locomotion, climbing, and primate evolution
E-mail: jhanna@osteo.wvsom.edu

✉ **Jandy Hanna, PhD**
Associate Professor and Vice-Chair
Department of Biomedical Sciences, WVSOM, 400 N. Lee St., Lewisburg, WV 24901, USA