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Research article

A Comparison of Stride Length and Lower Extremity Kinematics during Barefoot and Shod Running in Well Trained Distance Runners

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Abstract

Stride length, hip, knee and ankle angles were compared during barefoot and shod running on a treadmill at two speeds. Nine well-trained (1500m time: 3min:59.80s ± 14.7 s) male (22 ±3 years; 73 ±9 kg; 1.79 ±0.4 m) middle distance (800 m – 5,000 m) runners performed 2 minutes of running at 3.05 $m\cdot s^{-1}$ and 4.72 $m\cdot s^{-1}$ on an treadmill. This approach allowed continuous measurement of lower extremity kinematic data and calculation of stride length. Statistical analysis using a 2X2 factorial ANOVA revealed speed to have a main effect on stride length and hip angle and footwear to have a main effect on hip angle. There was a significant speed*footwear interaction for knee and ankle angles. Compared to shod running at the lower speed (3.05 $m\cdot s^{-1}$), well trained runners have greater hip, knee and ankle angles when running barefoot. Runners undertake a high volume (~75%) of training at lower intensities and therefore knowledge of how barefoot running alters running kinematics at low and high speeds may be useful to the runner.

Key words: Running mechanics, endurance, hip, knee, ankle.

Introduction

Well trained endurance athletes spend the majority (~75%) of their training time below the lactate threshold and a smaller (~15 – 20%) proportion of the time far in excess of lactate threshold (Seiler and Kjerland, 2006). Therefore, low intensity-high volume and high intensity-low volume training represents the majority of the training load for the endurance runner and subsequently, represents most (90 – 95%) of the exposure time which contributes to injury incidence. Given the repetitive nature of running, it is preferable to have running kinematics which can balance stress on biological tissue (e.g. muscles, tendons, bone) (Radin, 1986). Runners with a history of plantar fasciitis have greater vertical loading rates and impact peaks compared with healthy control participants during running (~3.7 $m\cdot s^{-1}$) (Pohl et al., 2009). Rearfoot strike, the predominate (~75%) foot strike pattern used by shod runners when running long distances (Hasegawa et al., 2007) is associated with a more extended lower limb and a more defined impact peak on contact with the surface. Wellenkotter et al. (2014) have reported an increase in cadence (reduction in stride length) to reduce loading to the plantar surface of the foot. Barefoot running appears to be associated with a sub-conscious reduction in stride length and an increase in knee flexion and ankle plantar flexion angles which is suggested to lower the impact peaks and loading rates experienced by the runner (Boyer and Derrick, 2015; De Wit et al., 2000; Derrick et al., 1998; Divert et al., 2005; Schubert et al., 2013). Compared to shod running at ~3.0 – 3.3 $m\cdot s^{-1}$, inexperienced runners are reported to have a ~7 - 8% reduction in stride length when running barefoot overland (Thompson et al., 2014; Thompson et al., 2015), whilst runners with a long history of barefoot running (n = 8), three of whom had run a marathon barefoot, demonstrate a similar (~6.4%) reduction in stride length during barefoot running on a treadmill (Squadrone and Gallozzi, 2009). Whilst many studies have reported a reduction in stride length during barefoot running in comparison to shod, few have investigated well-trained competitive runners (Bonacci et al., 2013; McCallion et al., 2014). Furthermore, there is a need to determine whether differences in lower extremity kinematics and stride length between shod and barefoot conditions are affected by the speed of running. If as has been reported (Schubert et al., 2013), a reduction in stride length favourably alters biomechanical factors associated with running injury, it is important to determine the relative intensity of running where the greatest benefits may reside. This is particularly important in light of research which suggests that the vertical ground reaction forces experienced by the runner are greater during jogging, characterised by a higher centre of gravity, than high speed running characterised by a forward lean (Keller et al., 1996). Furthermore, James (1978) identified 65% of running injuries to occur in runners engaged in repeated low loading (high mileage) on a daily basis and Vleck and Garbutt (1998) who reported the number running injuries to occur in competitive triathletes to be associated with the total distance covered in a week's training. Therefore knowledge of kinematic and stride length changes at low and high speeds when running shod or barefoot may be of value for the runner. Finally, there is a need to investigate changes in lower extremity kinematics and stride length in well-trained competitive runners, with previous exposure to barefoot running but who are not yet chronically trained. This need arises from the fact that acute studies using a short duration of running may observe the period when the runner can tolerate the higher impact of barefoot running without adjusting shod kinematics (Divert et al., 2005). Previous exposure to barefoot running may act as a form of familiarisation and provide a better representation of the difference in lower extremity kinematics between shod and barefoot running in well trained endurance run-

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ners. The aim of this study was to compare stride length, hip, knee and ankle angles in well trained distance runners, running in shod and barefoot conditions at speeds which represent low (3.05 $m \cdot s^{-1}$) and high (4.72 $m \cdot s^{-1}$) intensity running.

Methods

Participants

Nine male (22 ±3 y; 1.79 ±0.04 m; 73 ±9 kg) middle distance athletes who were members of the University of Limerick Athletics Club and competing (800m – 5,000m) at national varsity championship level participated in this study. Participants regularly participated in barefoot running as part of warm up or cool down routines but not during formal running sessions of low or high intensity. Participants had a mean 1500m personal best of 3 minutes 59.8 seconds ± 14.7 seconds and mean training volume of 100 ± 16km per week. Written informed consent was obtained from participants, and the study was approved by the University of Limerick research ethics committee and conducted according to the Declaration of Helsinki.

Test procedures

Participants ran for 5 minutes at a self-selected speed to warm up and familiarise themselves with the treadmill. Participants were then randomly assigned to undertake the barefoot or shod condition first in order to limit any potential order effects. Participants completed 2 minutes of running at 3.05 $m \cdot s^{-1}$ followed by a 2 minute rest period before undertaking 2 minutes of running at 4.72 $m \cdot s^{-1}$. Following 2 minutes of stationary rest the same procedure was repeated for the remaining barefoot or shod condition. To standardise the shod condition all participants wore a neutral running shoe from a well-recognised manufacture (New Balance; MR350WR).

Figure 1. Treadmill, camera and marker experimental set up.

To record kinematic data, participants wore tight fitting leggings and top to facilitate the motion capture system identifying the 11 markers placed on the left side of participants (Figure 1), 5 of which (Xiphoid process, greater trochanter, lateral femoral condyle, lateral malleolus and 5th metatarsal) were used for analysis. The left hand-rail of the treadmill (Powerjog; GXC 200) was removed in order to allow the four 3D Eagle infrared Motion Analysis Corporation cameras to identify the reflective markers (Figure 1). The motion analysis system underwent daily calibration. The camera orientation was determined by the known measurements of the L-frame markers. A wand algorithm was also used in daily calibration. Recording of participants begun 60 seconds into each condition and was recorded for 20 seconds at a sampling frequency of 200 Hz (Lenhart et al., 2014).

Data processing

Raw data was digitized using Cortex (version 3.0; Motion Analysis Corp., Santa Rosa, CA). Digitized frames were cubic joined and smoothed at a frequency setting cut off of 8 Hz (Kivi et al., 2001). From the 20 second time capture period, 5 consecutive strides within a coefficient of variance (5%) were utilised to obtain kinematic data for further analysis. Stride length was estimated using the distance measured between first and second initial contact of the left foot (5th metatarsal). Stride length was calculated as treadmill speed ($m \cdot s^{-1}$)/stride frequency (strides/s), where stride frequency is determined from the 3D data (xyz coordinates of the 5th metatarsal marker). Data was subsequently exported into Microsoft Excel 2010™. The exported data included the xyz coordinates of all markers, the position of all markers in relation to the L-frame and wand calibration, the acceleration and velocity of each marker and the hip, knee and ankle angles throughout the data capture.

Statistical analysis

A Shapiro-Wilk test was used to assess normality of the data. Values are reported as mean (SD) and min-max. A 2x2 factorial ANOVA was used to assess the main effects of speed, main effects of footwear and any interactions. Linear regression analysis was used to assess the relationship between change in knee angle and reduction in stride length. All statistical calculations were performed using SPSS statistical software V.22.0 (SPSS, Inc., Chicago, IL).

Results

Descriptive statistics for stride length and lower extremity kinematics are displayed in Table 1. There was a significant main effect of speed on stride length (F (1, 8) =1522, $p < 0.001$) and hip angle (F (1, 8) = 7.030, $p = 0.029$). Footwear had a significant main effect on hip angle (F (1, 8) =5.297, $p = 0.050$). There was a significant interaction between speed and footwear in relation to knee (F (1, 8) =7.240, $p = 0.027$) and ankle (F (1, 8) = 6.950, $p = 0.029$) angles. Individual relative percentage changes between barefoot and shod conditions at low (3.05 $m \cdot s^{-1}$) and high (4.72 $m \cdot s^{-1}$) velocities are displayed in Figure 1 and 2.

Discussion

The aim of this study was to observe stride length and lower extremity kinematics during shod and barefoot running, at low (3.05 $m \cdot s^{-1}$) and high (4.72 $m \cdot s^{-1}$) velocities, in well trained competitive runners with previous exposure to barefoot running. Speed had a significant

Table 1. A comparison of stride length and lower extremity angles during shod and barefoot running at 3.05 and 4.72 $\mathrm{m{\cdot}s^{-1}}$.

	Stride Length (m)	Hip Angle (°)	Knee Angle (°)	Ankle Angle (°)
		3.05 $\mathrm{m{\cdot}s^{-1}}$		
Shod	2.26 (.12)	128 (5)	142 (7)	97 (6)
	2.14 - 2.51	121 - 137	131 - 151	85 - 103
Barefoot	2.20 (.11)	129 (4)	147 (6)	100 (7)
	2.05 - 2.41	122 - 137	136 - 155	85 - 110
Difference	-.06 (.08)	1.4 (1.9)	5.3 (4.8)	2.7 (4.0)
	p = .051	p = .056	p = .011	p = .081
	d = .52	d = .31	d = .82	d = .42
		4.72 $\mathrm{m{\cdot}s^{-1}}$		
Shod	3.28 (.18)	126 (5)	142 (4)	99 (4)
	3.11 - 3.62	119 - 135	137 - 148	94 - 106
Barefoot	3.00 (.30)	126 (5)	141 (6)	95 (8)
	2.55 - 3.51	119 – 134	130 - 148	81 - 107
Difference	-.28 (.43)	.8 (2.4)	- .3 (6)	-3.9 (8.6)
	p = .107	p = .402	p = .910	p = .243
	d = .52	d = .16	d = .06	d = .65

Values reported as means (± SD), min – max, difference (p-value) and effect size (Cohen's d).

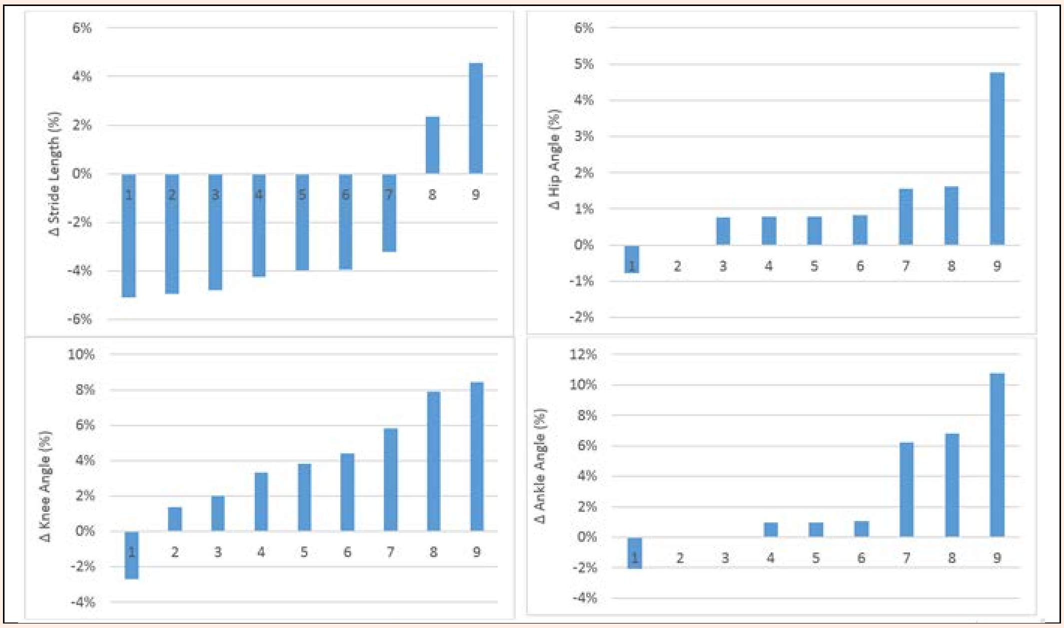

Figure 2. Individual changes (Barefoot – Shod) in stride length and lower extremity angles during barefoot and shod running at 3.05 $\mathrm{m{\cdot}s^{-1}}$.

main effect on stride length and hip angles ($p < 0.05$). Footwear had a significant main effect on hip angle ($p < 0.05$). The interaction between speed and footwear had a significant effect on knee and ankle angles ($p < 0.05$).

Compared to shod running, barefoot running (3.0 – 3.3 $\mathrm{m{\cdot}s^{-1}}$) leads to a reduction in stride length (6 – 8%) in inexperienced and those with a long history of barefoot running (Divert et al., 2005; Squadrone and Gallozzi, 2009; Thompson et al., 2014). We did not find a significant main effect of footwear on stride length in our study ($p = 0.060$). Inspecting the individual responses (Figure 2), 7 out of the 9 runners at the lower (3.05 $\mathrm{m{\cdot}s^{-1}}$) speed demonstrated a reduction in stride length (-3.2% – (-) 5.1%). The findings from these 7 runners are in agreement with Bonacci et al. (2013) who reported a statistically significant mean stride length reduction of ~3.3% in well trained runners (n = 22) of similar training status (~105 km per week) to the present investigation whilst running at 4.48 $\mathrm{m{\cdot}s^{-1}}$ ($p < 0.05$). The absence of a statistically significant reduction in the mean stride length and the smaller reduction in stride length from these 7 runners compared with that of previous literature may be due to our well-trained runners from an athletics club having had a 3 – 12% shorter stride length in the shod condition compared to the inexperienced and experienced barefoot runners in previous literature. This would be in agreement with the suggestion that high level runners have a shorter stride length than experienced but less accomplished runners (Youngren, 2005). It is also possible that the velocity of running (3.05 $\mathrm{m{\cdot}s^{-1}}$) is at the lower end of that used in previous literature which may encourage well trained runners to adopt a shorter stride. However, it does seem even at the faster speed (4.48 m/s) observed by Bonacci et al. (2013) that well-trained runners demonstrate a smaller reduction in stride length compared to their inexperienced counterparts. The individual change in

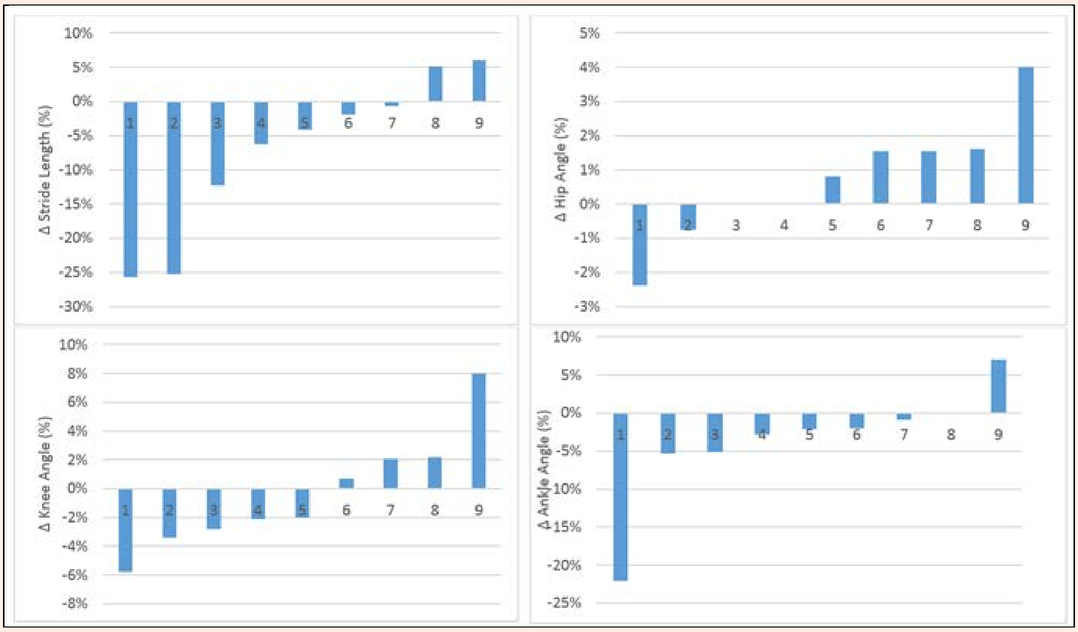

Figure 3. **Individual changes (Barefoot – Shod) in stride length and lower extremity angles during barefoot and shod running at 4.72 m·s^{-1}.**

stride length at the higher (4.72 m·s^{-1}) speed in our study is more heterogeneous (range: -26% - 6%; Figure 3) when comparing shod to barefoot running. This may be due to the range in event groups (800m – 5,000m) used such that at the lower speed (3.05 m·s^{-1}; 5.5 min·km^{-1}) the pace was 'low' for all athletes and results in more homogenous changes for the majority (n = 7) of the sample and at the higher speed (4.72 m·s^{-1}; 3.5 min·km^{-1}) the variability is greater due to a difference in efficiency running at this speed. For example, in the case of the 800m runner this may still have been a relatively low speed and in the case of the 5,000m runner this may have represented a greater percentage of maximum race speed. The heterogeneity of response may also be due to the small convenience sample (n = 9) used.

A reduction in stride length, although it would appear smaller in trained runners, may be advantageous for runners with high training volumes (~100km per week) as it has been shown to reduce impact peaks (Divert et al., 2005; Thompson et al., 2015) and loading rates (Hall et al., 2013) experience by the runner. A shorter stride length means the heel is located more underneath the centre of mass (COM) which reduces the amount of hip and knee flexion required (Heiderscheit et al., 2011). In contrast, over-striding may result in a more extended knee prior to foot contact adversely affecting weight acceptance and resulting in excessive breaking forces. This may increase repetitive tensile loads due to tissue elongation and prolonged eccentric muscle contraction (Lohman et al., 2011). The present investigation reports a main effect of speed (p = 0.029) and footwear (p = 0.050) on hip angle and a speed*footwear interaction for knee angle (p = 0.027). Inspection of the individual responses at the lower speed (Figure 2) reveals 7 out of 9 runners demonstrate an increase in hip angle (0.8% – 4%) and 8 out of 9 runners demonstrate an increase in knee angle (1.4% - 8.5%). As was the case with stride length, individual changes in hip and knee angle are less homogenous at the higher speed. At the lower speed, in those with an increase in knee angle and reduction in stride length (n = 7), 79% of the variance in knee angle increases was explained by the relative reduction in stride length. Our findings in relation to an increase in knee angle support and extend the findings of De Wit et al. (2000), Lieberman et al. (2010) and Braunstein et al. (2010) in habitually shod recreational runners and those of Bonacci et al. (2013) in well trained runners. The greater variability in hip and knee angle changes between shod and barefoot running at the higher speed may be a factor of the variable efficiency of 800m -5000m runners at the higher speed as discussed above. At the ankle joint, there was a significant speed*footwear interaction (p = 0.030). Inspection of the individual responses (Figure 2 and 3) suggests that at the lower speed, 8 out of 9 runners demonstrate no change or an increase in ankle angles (0% – 10.8%). Conversely, at the higher speed 8 out of 9 runners demonstrate no change or a reduction in ankle angles (0% - 22%). At the lower speed it would appear our results agree with Lieberman et al. (2010), Bonacci et al. (2013) and Thompson et al. (2015) who report an increase in plantar flexion angle at touch down during barefoot running. De Wit et al. (2000) suggest the reduction in stride length is a factor of the altered foot placement when moving from barefoot to shod running. Divert et al. (2005) and Ahn et al. (2014) report an increase in the pre-activation of the triceps surae muscles to accompany the increase in plantar flexion. The authors suggest this may enhance the capacity of the passive structures of the foot to absorb energy. Differences in ankle kinematics between studies may be linked to whether runners were habitually rear foot (RF), mid foot (MF) or fore foot (FF) strikers. The prevalence of RF or M/FF strike varies considerably depending on running velocity and the training status of the runners under investigation. RFS is the main (~75%) foot strike pattern used by shod runners when running long distances (Hasegawa et al., 2007), in contrast to sprinting where the initial contact is almost universally with the forefoot (Novacheck, 1998). Hasegawa et al. (2007) have reported the percentage of MFS's at the 15km point in a half marathon to increase from 19% to 36% when comparing runners finishing 200 – 250th to the top 50 runners. Our sample was drawn from an athletic club in which the runners had a training status of ~100km per week which may have led to the majority (n = 6) of the sample already having a M/FFS pattern and therefore demonstrating little change between conditions. Conversely, those with a RFS may have demonstrated an increase in plantar flexion when adopting a M/FFS strike which is consistent with the literature (Kurz and Stergiou, 2004). Without classifying the runner's foot strike pattern at the outset in the present investigation, these possible explanations, while plausible, remain speculative.

It is perhaps less surprising that there was no uniformity of differences in lower extremity kinematics between shod and barefoot conditions at the faster (4.72 $m \cdot s^{-1}$) speed, where runners increase stride length and adopt a more M/FFS in response to increasing velocity rather than footwear.

The variable differences in stride length and lower extremity kinematics when comparing shod and barefoot running is most likely a factor of the variability in methodologies used, the influence of inter subject variation inherent in small samples sizes (n = 8 – 30) and the training status of the runners under investigation. The duration of running is important, as initially runners can tolerate the higher impact of barefoot running without adjusting shod kinematics, characterised by RFS, before eventually adopting a more M/FFS (Divert et al., 2005). The use of a treadmill in the present study allowed us to ensure continuous running for a period of 1 minute prior to data capture which combined with the runners previous experience of barefoot running meant we could capture data that may have been more difficult using inexperienced runners on a track of restricted length. However, there is a possibility that in our investigation that 1 minute might not have been long enough to fully attenuate the habituation effects.

The downside to this approach is that the running velocity is not self-selected but instead controlled by the motor. The use of two fixed speeds meant that for some of our runners the low speed may have been too low and the higher speed not high enough. These speeds were chosen to encompass the entire sample. Furthermore, whilst we randomised the order of footwear, we did not randomise the order of running speed and this may have affected the results as increasing velocity from low to high for all participants may have led to progressive changes in kinematics separate to that of velocity alone. In an attempt to reduce inter-subject variation due to the experience and training status of the runner, we used a homogenous group from a University athletic club. However, with a small sample (n = 9) the influence of inter subject variation on mean changes is still evident (Figure 2 and 3) and this may in part be due to the range of middle distance (800 – 5,000m) athletes assessed

Conclusion

We report speed to have a significant main effect on stride length and hip angles in well trained runners with previous exposure to barefoot running. Furthermore, we report footwear to have a significant main effect on hip angle and a significant speed*footwear interaction to occur for knee and ankle angles. Due to the limited sample size we have discussed the individual relative changes at both speeds in an attempt to further explain the results of the statistical analysis. The magnitude of change in stride length among 7 runners at the lower speed (~3 - 5%) in our study is smaller than seen with recreational runners but in agreement with another study on well-trained runners (Bonacci et al., 2013). Well trained runners undertake a high volume (~75%) of training at lower intensities and therefore interventions which have the potential to favourably alter lower extremity kinematics warrant further investigation.

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Key points

- Barefoot and shod kinematics are examined in competitive track runners with a mean 1500m personal best of 3:59:80. Previous literature has not investigated competitive track runners.
- Compared to amateur runners, competitive track runners demonstrate a smaller reduction in stride length during barefoot running at ~3 m·s^{-1}.
- There is no difference in stride length or lower extremity kinematics when running at 4.72 m·s^{-1}.
- Given that competitive runners spend a large (~75%) amount of time training at lower speeds, interventions which favourably alter running kinematics may be advantageous for the prevention of injury.

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