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EFFECT OF OUTSOLE THICKNESS ON RUNNING BIOMECHANICS

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ABSTRACT Running shoes with increased or decreased sole thickness are postulated to improve running performance, besides to protect runners against high impact forces and running injuries. However, there is no evidence showing that running shoe developments emerging on the market help tackle running injuries. In this study, we compared the effect of different outsole thicknesses: (i) barefoot, (ii) minimalist and (iii) maximalist sports shoes on running biomechanics. Fifteen male subjects (age 23.19 ± 0.73 years old) who had regular exercises for at least 75 minutes per week were recruited to participate in this study. Participants had completed three minutes of running on a treadmill in each condition. Lower extremity kinetics and kinematics were analysed. There was no difference between maximalist running shoes and minimalist running shoes with respect to maximum vertical ground reaction force (VGRF) (p = 0.221), step length (p = 0.50) and cadence (p = 0.30). In addition, we observed longer ground contact time in maximalist running shoes (1.087 ± 0.115 s) when compared with minimalist running shoes (1.051 ± 0.105 s) (p = 0.007). On the other hand, runners had significantly higher knee flexion and adduction in minimalist shoes than maximalist shoes (p = 0.046). In conclusion, running in minimalist shoes, at least in a short period, produces greater running efficiency with shorter ground contact time but may result in a higher injury risk at the knee joint.

Keywords: minimalist, maximalist, kinematic, kinetic, biomechanics.

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1. INTRODUCTION

Running is one of the popular sport exercises due to its low cost, equipment-free and time-independent. In addition, it can improve our cardiorespiratory function, stamina and general well-being (Hulme et al., 2017; Mei et al., 2018; Lee et al., 2017). Therefore, the selection of running shoes is the foremost thing that a runner needs to do. However, various running shoe constructions could affect athletic performance-related and injury-related variables (Sun et al., 2020). Most modern running shoes available in the market are developed multiple features, such as increased cushioning and sole thickness, to decrease running-related injuries.. Sole thickness essentially influences the plantar sensation and running foot strike pattern between shod and barefoot conditions (Chambon et al., 2014; Law et al., 2019). The trend of running shoes can be further divided into minimalist and maximalist types of shoes. Maximalist shoes have higher cushioning for the midsole that is able to act as a mechanical stress absorber during running (Sinclair et al., 2015; Sinclair et al., 2016b). However, additional external loading caused by enhanced cushioning systems may alter lower extremity kinetic (Lieberman et al., 2010; Warne et al., 2014; Hall et al., 2013; Lohman III et al., 2011), kinematic (Bertelsen et al., 2013; Bonacci et al., 2014) and muscle activation patterns (DeMers et al. 2014) in turn has a detrimental effect on running economy (Sinclair et al., 2016c).

To address this issue, thinner and lighter structure shoes have gained increasing attention. Minimalist shoes have more prominent sole adaptability, low heel-to-toe drop, less cushioning, and lighter weight (Bonacci et al., 2013; Esculier et al., 2015; Pollard et al., 2018) to promote barefoot-like-running. However, despite the minimalist shoes are gaining popularity, whether running in a minimalist shoe could outperform the maximalist shoes to enhance running efficiency and injury prevention remains to be determined. Although some studies suggested that minimalist shoes provide significant improvements in the running economy compared to traditional shoes (Gillinov et al., 2015; Cheung & Ngai, 2016; Moore et al., 2014; Warne et al., 2014), others found no such effect (Hein et al., 2014; Bonacci et al., 2013). In addition, some contradicting results have also been reported on the influence of minimalist shoes on overuse injuries (Ridge et al., 2013; Ryan et al., 2014).

Hollander et al. (2015) indicated that a decrease in step length step rate during minimalist running could reduce impact force peak (Zadpoor et al., 2011; Pohl et al., 2009) and loading rates, which in turn, prevent impact-related-injuries (Tam et al., 2014; Hobara et al., 2012). Lieberman et al. (2010) revealed that minimalist footwear could minimise the incidence of chronic running injuries to the runners. Squadrone & Gallozzi (2009) showed a reduction in the impact peak of ground reaction force for minimalist shoes. Conversely, several studies had opposite findings that wearing minimalist footwear will result in greater VGRF compared to maximalist footwear (Willy & Davis 2013; Kulmala et al., 2018; Agresta et al., 2018). Sinclair et al. (2015) highlighted no significant results for the ground reaction forces between the different outsole thicknesses of footwear. However, the Achilles tendon loads were higher in minimalist footwear than cushioning shoes, which indicated that minimalist shoes might increase the risk of Achilles tendon injury. Other findings include the knee joint loading during gait. When running in minimalist shoes, the peak knee abduction moment is lower than running in maximalist shoes (Sinclair et al., 2015; Bonacci et al., 2013). Another variable that has been evaluated is the loading rate during the running gait. The most consistent finding is that highly cushioning shoes will increase the instantaneous loading rate (Sinclair et al., 2016b; Aminaka et al., 2018; Kulmala et al., 2018).

Due to inconsistent findings in the literature, no conclusive finding exists on the effectiveness of different outsole thicknesses on running biomechanics. Therefore, the biomechanical effects in minimalist and maximalist footwear deserve further investigation. The objective of this study was to investigate the relations between different outsole thickness and treadmill running biomechanics in 15 regular male exercisers. In addition, two varying minimalist and maximalist shoe models were compared with barefoot conditions at the fixed running speeds.

2. MATERIALS AND METHODS

Fifteen male subjects (age 23.19 ± 0.73 years, height 173.75 ± 6.49 cm and weight 65.55 ± 10.05 kg) were recruited in this study. All of them underwent a minimum of 75 minutes/week of vigorous activities such as running, swimming, soccer, badminton, basketball and volleyball that need a significant amount of effort and can increase the heart rate and breathing of the exerciser (World Health Organization, 2019). All subjects were free from musculoskeletal disease and had no major surgery in the past six months. Each subject was given informed consent before involving in the study.

2.1 Experiment Procedure

Subjects ran at 8 km/hr (Gazendam et al., 2007; Fredericks et al., 2015) on H/P Cosmos Instrumented Treadmill, Model: TLA10004681 embedded with force plates (Figure 1) for three minutes. Before being tested, each subject was given three minutes of warmed-up running from lower speed and gradually increasing to 8 km/hr. Subjects completed three successful trials in each footwear condition: minimalist (MIN), maximalist (MAX) and barefoot with socks (BF). The order that subjects ran in different footwear conditions was randomised. Markers were placed at the various joints of the lower extremity: pelvic, knee, ankle, heel and the fifth metatarsal, as shown in Figure 2. After three minutes terminated, each subject was given a resting period of 10 minutes. The same trial was repeated for the second and third pairs of footwear.

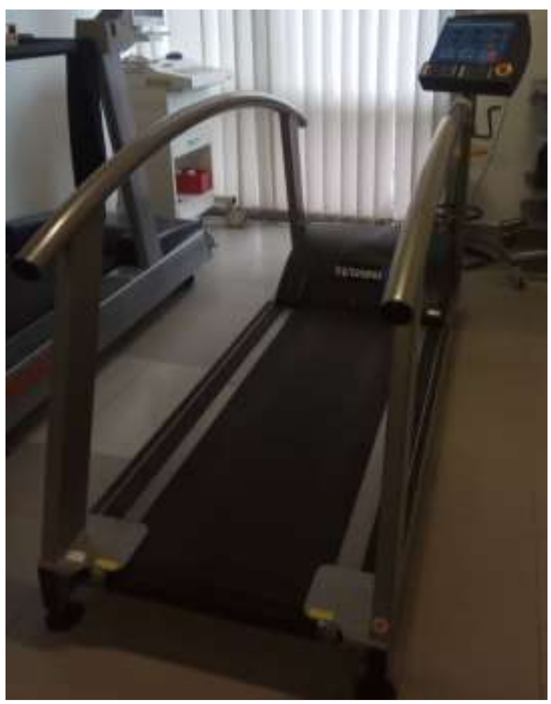

Figure 1. H/P Cosmos Instrumented Treadmill embedded with force plates

Figure 2. Markers placement on the sagittal plane (left) and back view of frontal plane (right)

While the subjects performed running tests on the treadmill, Kistler Gaitway Software was used to obtain gait data such as maximum VGRF, step length, cadence and contact time. Two cameras were set up for kinematic analysis to record the video at the subject's side and back view running, respectively. One camera was placed at the posterior view of the subject, while another camera was placed at the sagittal view of the right leg. Thus, both filmed frontal and sagittal views were synchronised during data acquisition. Subsequently, the recorded videos were used to capture the kinematic movement of the subjects during running. The knee joint kinematics: flexion angle (Nagano et al., 2015) and adduction angle (Aksenov and Klishkovskaya, 2017) were further analysed using Kinovea software. The Newton-Euler inverse dynamic method was adopted to calculate the knee flexion and adduction moment (Chowdhury & Kumar, 2013).

2.2 Experimental Footwear

This study focused on testing the maximalist (Power brand) and minimalist (Merrell Vapor Glove) footwear. Both maximalist and minimalist footwear is shown in Figure 3. The characteristics of the footwear are summarised in Table 1.

Figure 3. Side view of maximalist (left) and minimalist (right) footwear

Table 1. Summary of the footwear characteristics

Minimalist					
Size	Length (cm)	Width (cm)	Mass (kg)	Thickness (mm)	Heel Drop (mm)
UK 8.5	29.00	10.50	0.18	8.00	0.00
UK 9.5	29.00	10.60	0.19		

Maximalist						
Size	Length (cm)	Width (cm)	Mass (kg)	Thickness (mm) Toe	Thickness (mm) Heel	Heel Drop (mm)
UK 8	29.50	10.60	0.31	20.00	24.00	4.00
UK 9.5	30.40	10.70	0.32			

Besides, the hardness of both minimalist and maximalist shoes was measured using Shore A Durometer. The hardness measurement was taken around 1 cm radius from the locations: (i) 70% of shoe length from the forefoot and (ii) 12% of shoe length from the hindfoot (Nin et al., 2016). Therefore, the hardness reading for both minimalist and maximalist footwear is tabulated in Table 2.

Table 2. Hardness measurement summary for minimalist and maximalist

Hardness Measurement Locations	Minimalist		Maximalist	
	UK 8.5	UK 9.5	UK 8	UK 9
Hardness at 12% (HA)	41.1	40.0	33.3	35.3
Hardness at 70% (HA)	44.2	42.8	36.0	36.4

2.3 Statistical Analysis

All the kinematic and kinetic data were normalised to eliminate the inter-individual differences and reduce the bias of subjects' stature. A statistical test is needed to study the relationship within the parameters with different conditions of the footwear from the same subject. The statistical test helps to provide quantitative decision making between two conditions. It uses the mean and standard deviation and measures the variability within a set of data. In this project, the Wilcoxon signed-rank test was performed to test the parameters andsignificant results. The statistical tests were performed using Statistical Package for the Social Sciences (SPSS), version 16. The statistical significance was set at $p < 0.05$.

3. RESULTS AND DISCUSSION

Figure 4 shows the graph of maximum VGRF for one gait cycle for all three footwear conditions of a recruited subject. Two different levels of peaks are shown on the graph. The first lower peak initiates the heel striking on the ground, while the second peak contributes the highest force during loading response.

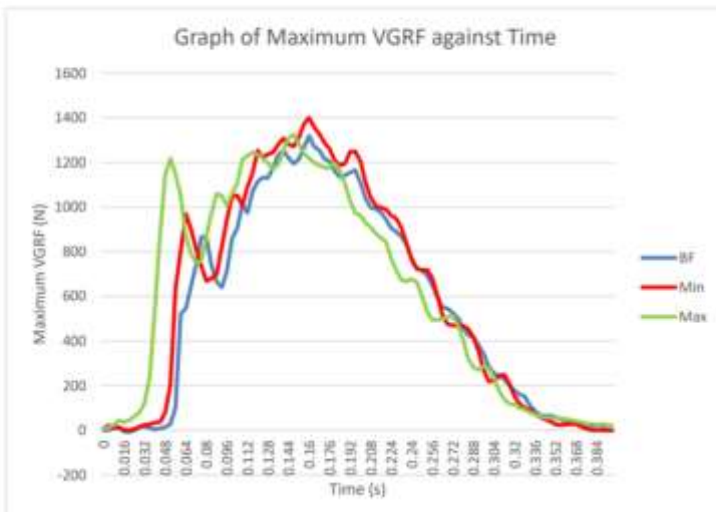

Figure 4. Graph of maximum VGRF against time for BF, MIN and MAX.

Table 3 shows the average results of normalised maximum VGRF for barefoot, minimalist footwear and maximalist footwear for all 15 male subjects. In agreement with Kulmala et al. (2018), running with minimalist footwear has the highest VGRF, followed by maximalist footwear and the condition providing the least maximum VGRF is barefoot. Indeed, a previous study also showed a higher peak on VGRF with barefoot running than shod running with different midsole thicknesses (Chambon et al., 2014). From Table 4, a significant increase was observed for minimalist footwear (3.41%, $p = 0.013$) but no significant difference for maximalist footwear (1.68% increase, $p = 0.198$). Moreover, no significant effect was observed between minimalist and maximalist footwear (Min>Max, $p = 0.221$). During running, the peak amplitude of VGRF was approximately 2-3 times body weight. VGRF parameter has been associated as a cause of running-related injuries at the lower extremities, such as patellofemoral pain, iliotibial band syndrome and tibial stress syndrome (Ferber and Macdonald, 2014). Minimalist footwear has been implicated to potentially increase the risk of musculoskeletal injuries (Sinclair et al., 2016a).

Table 3. Normalised kinematic and kinetic data across different outsole thicknesses

	BF	MIN	MAX
Maximum VGRF	2.021±0.189	2.090±0.164	2.055±0.169
Knee Flexion Moment	0.424±0.048	0.482±0.037	0.447±0.041
Knee Adduction Moment	0.284±0.024	0.279±0.029	0.248±0.028
Step Length	0.885±0.047	0.915±0.042	0.913±0.043
Cadence (per min)	0.832±0.046	0.816±0.029	0.811±0.035
Contact Time (s)	1.032±0.103	1.051±0.105	1.087±0.115

Table 4. Comparison of parameters across different outsole thicknesses

	Paired conditions	*p*-value
Maximum VGRF	BF & MIN	0.013*
	BF & MAX	0.0198
	MIN & MAX	0.221
Knee Flexion Moment	BF & MIN	0.028*
	BF & MAX	0.345
	MIN & MAX	0.046*
Knee Adduction Moment	BF & MIN	0.463
	BF & MAX	0.046*
	MIN & MAX	0.046*
Step Length	BF & MIN	0.020*
	BF & MAX	0.008*
	MIN & MAX	0.496
Cadence	BF & MIN	0.109
	BF & MAX	0.017*
	MIN & MAX	0.300
Contact Time	BF & MIN	0.134
	BF & MAX	0.007*
	MIN & MAX	0.007*

This study also found that the peak knee flexion moment was higher when wearing both footwears compared to barefoot (Table 3). Statistical analysis revealed a more significant peak knee flexion moment wearing minimalist (13.86%, $p = 0.028$) and maximalist footwear (5.42%, $p = 0.345$) compared to barefoot. A similar finding was reported by Chambon et al. (2014), where barefoot running compared to shod running with midsole induced lower knee flexion during the stance phase. A significant difference was found (7.83%, $p = 0.046$) while comparing minimalist footwear with maximalist footwear. Bonacci et al. (2013) and Borgia & Berker (2019) provide support for these results. A smaller knee flexion angle brings to the lower moment arm and reduces the stress across the patella-femoral joint during barefoot running. Higher peak knee flexion moment is associated with greater patellofemoral joint loads, which subsequently can increase the incidence of knee pathologies such as patellofemoral pain.

Knee adduction moment has been linked to indicator measurement of medial-lateral knee stress distribution (Birmingham et al., 2007). Opposite to knee flexion moment, the greatest knee adduction moment in barefoot was found. Knee adduction moment in maximalist footwear was significantly lower than both barefoot and minimalist footwear ($p = 0.046$). Greater knee adduction moment is able to increase the risk of knee injury especially sprains and pain associated with knee osteoarthritis (OA) (Radzimski et al., 2012).

It has been previously revealed that a smaller number of steps during running reduces the impact force peak and loading rates (Hobara et al., 2012). This finding led to protection against the risk of running injuries such as Achilles tendon injury (Hollander et al., 2015). Step length is important to indicate the number of steps used to complete a certain distance. Both minimalist and maximalist footwear increase step length as cushioning increased ($p = 0.02$ and $p = 0.008$, respectively). The minimalist footwear condition leads to higher step length and higher cadence when compared with maximalist footwear. However, both footwears have no significant differences in step length and cadence ($p = 0.496$ and $p = 0.30$, respectively). In agreement with the observation of other studies (De Wit et al., 2000; Hsu et al., 2012; Law et al., 2019), we found significant differences in step length between barefoot running and all footwear running conditions.

Ground contact time in maximalist footwear was significantly larger than both minimalist and barefoot conditions (p=0.007), while no statistical significance was found in minimalist and barefoot conditions. This biomechanical analysis supports the previous studies in the field (Squadrone et al., 2015; Aminaka et al., 2018; Kulmala et al., 2018; Law et al., 2019). Interestingly, our observations are in line with those from midsole studies; the contact time increased with the midsole thickness (Chambon et al., 2014). Thus, the thickness of the sole may delay the foot contact with the ground and need some time to be deformed, in turn, prolong the stance phase duration. Overall, the present investigation suggests that minimalist footwear and barefoot running lead to increase running efficiency with shorter ground contact time correlates with higher cadence when compared with maximalist shoes (Gillinov et al., 2015; Sun et al., 2020).

4. CONCLUSION

In this study, outsole thickness effectively influences running performance-related and injury-related variables. Ground contact time was the highest during maximalist footwear running and decreased with thinner outsole footwear. It indicates that minimalist footwear may improve running efficiency in comparison to maximalist footwear. However, our results revealed that higher joint moments at the knee while running in minimalist footwear might increase the risk of knee pain and injury. Further investigation on other shoe constructions needs to be conducted, such as cushioning stiffness, heel to toe drop, heel flare and insole to optimise the running efficiency and prevent running-related injuries.

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