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Title: Differences in stride length and lower limb moments of recreational runners during over-ground running while barefoot, in minimalist and in maximalist running shoes.

Authors:

Richard Stoneham, PhD[1]

Gillian Barry, PhD[1]

Lee Saxby, BSc[2]

Lauryn Waters[3]

Mick Wilkinson, PhD[1]

[1] Department of Sport, Exercise and Rehabilitation, Northumbria University, UK

[2] LeeSaxby.com, Suffolk House, Louth, Lincolnshire, UK

[3]Harton Academy, South Shields, UK

Corresponding author:

Dr Mick Wilkinson, Sport, Exercise and Rehabilitation, Northumbria University, Newcastle-upon-Tyne, NE1 8ST, mic.wilkinson@northumbria.ac.uk, +44191 225 7097

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Abstract.

The aim of this study was to compare stride length, and peak knee and ankle moments during over ground running performed barefoot, in minimalist and in maximalist shoes. Fifteen (10 male, 5 female) recreational endurance runners who habitually wore conventional-cushioned shoes participated. Stride length as well as knee and ankle moments were recorded during running on an indoor runway at a self-selected comfortable speed while barefoot, in minimalist and in maximalist shoes. Each condition was performed on a different day and the order of conditions was randomised and counterbalanced. Differences in stride length, and peak knee and ankle moments between conditions were examined with ANCOVA with speed as the covariate. After adjusting for speed, there was a significant increase in stride length from barefoot (1.85$\pm$0.01m) to minimalist (1.91$\pm$0.01m) to maximalist shoes (1.95$\pm$0.01m). Peak knee flexion moment also increased significantly from barefoot (2.51$\pm$0.06Nm$\cdot$kg^{-1}) to minimalist (2.67$\pm$0.06Nm$\cdot$kg^{-1}) to maximalist shoes (2.81$\pm$0.06Nm$\cdot$kg^{-1}). Results then showed peak dorsiflexion moment was lower in the maximalist condition (2.34$\pm$0.04Nm$\cdot$kg^{-1}) than both the barefoot (2.57$\pm$0.04Nm$\cdot$kg^{-1}) and minimalist condition (2.66$\pm$0.03Nm$\cdot$kg^{-1}). Results suggest that stride length and peak knee flexion moment increase from barefoot to minimalist to maximalist shoes, and ankle moment significantly changes as a function of footwear. This indicates that footwear can influence self-selected stride length and peak lower limb loads that are a risk factor for running-related knee injury.

Introduction.

Injury incidence in running ranges from 19.4-79.3% (van Gent et al., 2007). The knee is the most injured site, comprising 42.1% of all running-related injuries (Taunton et al., 2002; van Gent et al., 2007). Patellofemoral Pain Syndrome is a common running-related knee injury (Taunton et al., 2002) and has been linked to high knee flexion moments (Bonacci, Vicenzino, Spratford, & Collins, 2014; Farrokhi, Keyak, & Powers, 2011). Previous work has manipulated spatiotemporal variables such as stride length and stride frequency to reduce loads associated with knee injury (Edwards, Taylor, Rudolphi, Gillette, & Derrick, 2009; Firminger & Edwards, 2016; Heidercheit, Chumanov, Michalski, Willie, & Ryan, 2011). A systematic review suggests that an increased stride frequency (and therefore reduced stride length) improves shock attenuation, reduces the impact transient of the ground reaction force and lowers energy absorbed at the knee (Schubert, Kempf, & Heidercheit, 2014). Firminger and Edwards (2016) reported significantly reduced peak knee flexion moment when stride length was reduced to 90% of preferred stride length, and Lieberman, Warrener, Wang & Castillo (2015) showed increased posterior braking forces with reduced stride frequency and increased stride length suggesting a mechanistic link between stride length and running kinetics. Reducing stride length appears effective for reducing knee joint loading and could reduce injury risk at this frequently injured joint.

Footwear choice is another factor that can influence stride length and knee joint loads. Shorter stride length when running barefoot and in minimalist footwear compared to conventional cushioned shoes have generally been reported (Bonacci et al., 2014; de Wit, de Clercq, & Aerts, 2000; Divert, Mornieux, Baur, Mayer, & Belli, 2005; Kerrigan et al., 2009; Squadrone & Gallozzi, 2009). Differences in ground reaction force characteristics and knee joint loading have also been reported when running in minimalist shoes. Sinclair (2014) reported significant reductions in knee joint load when barefoot and in barefoot inspired shoes compared to conventional cushioned shoes. A more recent study (Bonacci et al., 2018) reported that 10% above preferred cadence in conventional shoes, preferred cadence in minimalist shoes, and 10% above preferred cadence in minimalist shoes all reduced patellofemoral joint stress by 16%, 15% and 29% respectively, compared to preferred cadence in conventional shoes. At a fixed running speed, increasing stride frequency necessarily reduces stride length, so Bonacci et al's (2018) data suggest a reduction in stride length by any means could reduce patellofemoral load. In addition to barefoot/minimalist versus conventional shoe comparisons, evidence also suggests differences between actual barefoot running and running in barefoot inspired/minimalist footwear. Bonacci et al (2013) showed significantly higher stride frequency and significantly lower stride length and peak flexion angle, joint moment, power absorption and negative work at the knee compared to a minimalist shoe. Moreover, Chambon, Delattre, Gueguen, Berton, and Rao (2014) showed lower maximal knee joint moments when barefoot than when running in 3mm thick minimalist shoes with 0mm and 4mm midsole thickness, suggesting that even a thin sole can alter aspects of gait related to knee injury risk. Neither stride length nor stride frequency were measured in this study.

However, changes in footwear from conventional to barefoot has been shown to alter the distribution of load in the lower limbs. Sinclair (2014) compared the effects of barefoot and cushioned shoe conditions on the distribution of load in the lower limbs and reported that running in conventional cushioned shoes significantly increased ankle moment and Achilles tendon load suggesting an increased potential for injury at the ankle joint. These types of findings lead authors such as Ryan et al. (2013) to investigate the effects of running in minimalist shoes on injury rates and conclude that clinicians should exercise caution when prescribing minimalist shoes as a result of the increased injury risk. However, in a more recent study, Yang et al. (2020) compared 12 weeks of minimalist shoe running to 12 weeks of gait training with minimalist shoes. They reported ankle plantarflexion moment increased for the gait retraining group post intervention, but importantly by combining minimalist footwear and gait retraining they attenuated peak impact force and loading rate. This highlights that while running in minimalist shoes might redistribute loading, if undertaken alongside a systematic gait transition, the likelihood of injury related to loading factors can be reduced.

In contrast to minimalist shoes, heavily-cushioned (or ‘maximalist’) footwear have been advocated to provide additional shock attenuation. Studies investigating the influence of maximalist shoes on knee loading and related aspects of gait are few. Sinclair, Richards, Selfe, Fau-Goodwin, and Shore (2016) reported lower patellofemoral forces in a minimalist shoe compared to both a conventional and maximalist shoe, but no difference between conventional and maximalist shoes. Chan et al. (2018) reported no difference in average or instantaneous vertical loading rate or stride length and foot strike angle between traditional and maximalist running shoes. Neither study compared peak knee and ankle moment or compared stride length between barefoot, minimalist and maximalist shoes. Given that barefoot and minimalist footwear have been shown to reduce stride length and knee flexion moments compared to conventional cushioned shoes, maximalist shoes, at the opposite end of the cushioning spectrum, might increase stride length by comparison and could, also, increase knee joint loads.

To date, conclusions about the effects of barefoot, minimalist and maximalist shoes on lower limb joints have been based on cross comparisons between studies. Such comparisons and subsequent conclusions are limited by confounding factors introduced by inconsistent sample demographics and habituation protocols. This study is the first of its kind to compare these three running conditions in a sample of habituated recreational runners and will clarify the effects of running barefoot, in minimalist and maximalist footwear on stride length and joint loads associated with injury. The aim of this study was to compare stride length as well as peak knee and ankle moments during over-ground running performed barefoot, in minimalist and in maximalist shoes. It was hypothesised that stride length would increase from barefoot to minimalist to maximalist shoes, that peak knee flexion moment would increase from barefoot to minimalist to maximalist shoes and peak ankle dorsiflexion moment would decrease from barefoot to minimalist to maximalist footwear.

Method

Participants

With institutional ethics approved, 15 recreational runners (10 male, 5 female) participated. Mean and SD age, stature and mass were 25±6 yrs, 1.74±0.1 m and 69±10.9 kg. Inclusion criteria were aged 18-45 years, no previous experience of barefoot, minimalist, or maximalist shoe running, and participation in endurance running more than once per week as part of their exercise regime, with one run lasting at least 30 minutes. Participants were excluded if they had an injury to the lower limbs in the previous six months or any condition that could affect their normal running gait.

Design

A repeated-measures design was used to assess the effect of footwear condition (barefoot, minimalist and maximalist shoes) on spatiotemporal variables and lower-limb kinetics of the dominant leg during over ground, indoor running. Participants were provided with a short-sleeved compression top and shorts to improve skeletal representation in biomechanical modelling. Footwear conditions were performed on separate days at a similar time of day within each participant, with sessions separated by 24 hours. The order of footwear conditions was counterbalanced and participants were instructed to be well rested before each session. Reflective markers were attached in ‘Plug-In gait’ formations to assess lower-limb kinematics and kinetics of the dominant limb. Participants were habituated to each footwear condition with a 30-minute self-paced run around an indoor track. After habituation and instruction to maintain the same comfortable self-selected pace, participants ran over a 20-m runway through a gait analysis laboratory where kinematic data were captured by 14 optoelectronic cameras, and kinetic data were captured by four embedded force plates. Electronic timing gates (Brower timing gates, Utah, USA) placed in the data capture area (2.7m apart) were used to record speed in each trial.

Footwear

In the minimalist condition, participants ran in a VivoBarefoot® Stealth II, a minimalist shoe with a non-cushioned and highly flexible 4mm EVA sole, thin mesh upper, and 0mm heel-to-toe drop height (Figure 1, left). The maximalist shoe was a Hoka One One Clifton 2, a shoe with an enlarged CMEVA midsole, a 29mm heel stack, 24mm toe stack, and 5mm heel-to-toe drop (Figure 1, right). The choice and definition of the shoes as minimalist and maximalist was based on the rating scale of Esculier et al. (2015) that results in a minimalist index of 88% and 24% for the VivoBarefoot Stealth II and Hoka One One Clifton 2 respectively.

Figure 1 about here

Procedures

Before data collection, anthropometric measures were recorded for use in biomechanical modelling (stature (mm), mass (kg), bilateral-leg length (mm), and knee and ankle joint width (mm)). Subsequently, participants had markers (Ø=14mm) attached in a 'Plug-In Gait' formation to facilitate the assessment of lower-limb joint kinematics and kinetics. Anatomical locations of the 'Plug-In Gait' model were as follows: bilateral anterior-and posterior-superior iliac spines; the bilateral distal-lateral thigh; bilateral femoral-lateral epicondyle; the bilateral distal-lateral lower limb; the bilateral lateral malleoli; the left/right toe (dorsal aspect of the second metatarsal head) and the calcaneus.

Kinematic data were captured by 14 calibrated infrared cameras (12 x T10 and 2 x T20, Vicon MX, Oxford, UK) at 200Hz. Four force plates (OR6-7, AMTI, Watertown MA, USA) captured data at 1000Hz. Force plates were connected to an amplifier (MiniAmp MSA-6, AMTI, Watertown MA, USA) which amplified force with a gain of 1000. Amplified signals from force plates were connected to one of two available Vicon MX Giganet core processing units (Vicon, Oxford, UK) by way of a patch box and analysed in Vicon Nexus software (version 1.7).

Data analysis

Initial contact and toe-off events were identified when the magnitude of the GRF crossed a 20N threshold. Kinematic data were filtered at 25Hz using a fourth-order Butterworth filter with zero lag. Newton-Euler inverse dynamics approach was used to resolve external joint moments in the proximal segment co-ordinate system. Data were normalised to the stance phase in Polygon Authoring Tool (3.5.1, Vicon, Oxford, UK).

Statistical analysis

Data were analysed using MiniTab 19. Assumptions of normality, uniformity of error and sphericity were checked and verified. Subsequently, repeated-measures ANCOVA examined differences in stride length, and peak knee and ankle flexion moment between barefoot, minimalist shoe and maximalist shoe conditions, adjusting for differences in running speed (covariate) between the conditions. Significant main effects were explored using post-hoc 95% confidence intervals adjusted for multiple comparisons using the Fisher LSD method.

Results.

There was no significant main effect of footwear on speed ($F_{2,42}$ = 0.95, p = 0.39). Mean and SD running speed for barefoot, minimalist and maximalist were conditions were 2.48±0.38m·s^{-1}, 2.6±0.43m·s^{-1} and 2.68±0.37m·s^{-1} respectively.

Differences in stride length between barefoot, minimalist and maximalist conditions.

There was a significant main effect of footwear condition on stride length ($F_{2,44}$ = 13.52, p < 0.001). Adjusted to a common speed of 2.59m·s^{-1}, mean and SE stride length was 1.85±0.01m, 1.91±0.01m and 1.95±0.01m when barefoot, in minimalist and in maximalist shoes respectively. Mean stride length was shorter when barefoot than in minimalist shoes (-0.05m; 95% CI -0.08 to -0.02m) and maximalist shoes (-0.09m; 95% CI -0.12 to -0.06m). Stride length was shorter in minimalist than in maximalist shoes (-0.04m; -0.07 to -0.02m). Differences between conditions are illustrated in Figure 2.

Figure 2 about here

Differences in peak knee flexion moment between barefoot, minimalist and maximalist conditions.

There was a significant main effect of footwear condition on peak knee flexion moment ($F_{2,44}$ = 4.96, p = 0.015). Adjusted to a common speed of 2.59 m·s^{-1}, mean and SE peak knee flexion moment was 2.51±0.06Nm·kg^{-1} when barefoot, 2.67±0.06Nm·kg^{-1} in minimalist shoes and 2.81±0.06Nm·kg^{-1} in maximalist shoes. Mean peak knee flexion moment was lower when barefoot than in minimalist shoes (-0.16Nm·kg^{-1}; 95% CI -0.30 to -0.02Nm·kg^{-1}) and maximalist shoes (-0.30Nm·kg^{-1}; 95% CI -0.50 to -0.14Nm·kg^{-1}). Minimalist shoes resulted in lower peak knee flexion moment than maximalist shoes (-0.14Nm·kg^{-1}; 95% CI -0.28 to -0.01Nm·kg^{-1}). Differences between conditions are illustrated in Figure 3.

Figure 3 about here

Differences in peak dorsiflexion moment between barefoot, minimalist and maximalist conditions.

There was a significant main effect of footwear condition on peak dorsiflexion moment ($F_{2,44}$ = 13.89, p = 0.001). The barefoot condition (2.57±0.04Nm·kg^{-1}) and minimalist condition (2.66±0.03Nm·kg^{-1})

did not differ (0.09Nm·kg^{-1}; 95% CI -0.02 to 0.19Nm·kg^{-1}). However, peak dorsiflexion moment in the maximalist condition (2.34$\pm$0.04 Nm·kg^{-1}) was significantly lower than the barefoot condition (-0.23Nm·kg^{-1}; -0.35 to -0.11 Nm·kg^{-1}) and the minimalist condition (-0.32Nm·kg^{-1}; -0.42 to -0.22Nm·kg^{-1}). Differences between conditions are illustrated in Figure 4, and a summary of all comparisons is provided in table 1.

Figure 4 about here

Table 1 here

Discussion.

The aim of this study was to compare stride length, and peak sagittal knee and ankle moments during over-ground running performed barefoot, wearing minimalist shoes and wearing maximalist shoes. Both stride length and peak knee flexion moment increased from barefoot to minimalist to maximalist shoes. Peak dorsiflexion moment was lower in the maximalist condition than both barefoot and minimalist conditions. These data suggest that running in maximalist shoes increases stride length and loading at the knee joint. This highlights the importance of footwear choice and the potential for a minimalist shoe design to reduce loading at the knee joint, the most commonly injured joint in the runner's lower limbs (Van Gent et al., 2007).

While some previous studies have compared kinematic, spatiotemporal and kinetic variables between barefoot and minimalist shoes and others have compared minimalist and maximalist shoes, this is the first comparison of barefoot, minimalist and maximalist conditions in a single study. In agreement with Bonacci et al. (2013), we observed a reduction in stride frequency and an increase in stride length from the barefoot to the minimalist shoe condition. Peak knee flexion moment increased from the barefoot to the minimalist shoe condition in agreement with the findings of Chambon et al. (2014). The changes in stride length and frequency, and the increase in knee load suggest that even a very thin sole (4mm) is sufficient to alter self-selected gait characteristics, and confirms the conclusions of Bonacci et al. (2013) that running in a minimalist shoe is not the same as running barefoot.

In terms of knee flexion moment however, running in a minimalist shoe was better than running in a maximalist shoe. We observed a significantly higher peak knee flexion moment in the maximalist shoe compared to both minimalist shoe and barefoot conditions. Stride length was also longer and stride frequency lower in the maximalist shoe. The increased knee load from minimalist to maximalist shoes supports previous work by Sinclair et al. (2016) that reported higher patellofemoral joint stress in maximalist compared to minimalist shoes. Stride length and frequency were not recorded, although a more recent study showed higher self-selected stride frequency and lower patellofemoral stress in minimalist shoes compared to conventional cushioned shoes (Bonacci et al., 2018). The same study showed knee loads could be further reduced in both minimalist and conventionally cushioned shoes by increasing preferred stride frequency by 10%. As previously stated, at a fixed speed, an increase in stride frequency reduces stride length and vice versa. It therefore appears that stride length is an independent factor related to knee joint load in running, and that moving from barefoot to minimalist to maximalist shoes gradually increases stride length and peak knee flexion moment. Given the observed reductions in knee joint load, it is tempting to suggest that runners suffering from injury at the knee underpinned by increased knee joint loads consider a minimalist shoe design. Caution should be taken in making such a recommendation however. This study examined kinetics during a single stance phase and, while knee moment was reduced moving from maximalist, to minimalist to barefoot conditions, the accompanying reduction in stride length, and therefore increase in stride frequency, might increase cumulative load over any given distance due to the increased number of loading cycles (Firminger and Edwards, 2016; Firminger et al., 2020). Increased cumulative load could offset the decreased load per stride at the knee and, given the increase in ankle moment observed, also increase the risk of injury at the ankle and Achilles.

The gradual decrease in stride length from maximalist shoes through to barefoot could be regulated by plantar-sensory feedback about braking forces. Previous work by Wilkinson et al. (2018) found that increased subjective plantar sensation via textured insoles resulted in reduced stride length, increased stride frequency and reduced vertical loading rates. Though speculative, it is possible that plantar sensation of impact force decreases from barefoot to minimalist to maximalist shoe conditions with a resulting increase in stride length and reduction in stride frequency. In agreement with the work of Kram and Taylor (1990), increasing stride length/reducing stride frequency increases ground contact time and lowers the energetic cost of running which, if risk of injury is perceived to be low, is a driving force in gait selection. Exploring the possible influence of plantar sensation alterations with different footwear conditions and the influence on stride length was beyond the scope of the present study.

Changing from maximalist to minimalist or barefoot increased the peak plantarflexion moment. Sinclair (2014) also reported a significant increase in ankle moment as well as Achilles tendon force when comparing cushioned footwear to barefoot running. This highlighted the potential for increased risk of injury due to an increased Achilles tendon and ankle load. Recently, Yang et al. (2020) reported that a 12-week gait retraining intervention in minimalist shoes attenuated peak impact force and loading rate compared to running in minimalist shoes without gait retraining. The authors suggested that additional changes induced by gait retraining might reduce the likelihood of injury compared to those that immediately transition to minimalist footwear. The findings of previous work and the current study suggest that, running in a minimalist shoe shifts loading from the knee to the ankle which, in conjunction with appropriate gait retraining, might reduce knee injury risk. However, as suggested by Yang et al. (2020), it is recommended that such a transition is progressive and under the supervision of a running coach educated in gait retraining, and that a potential increase in cumulative load previously discussed also be held in mind.

A factor to consider in the interpretation of the key findings is that participants ran at different average speeds in each footwear condition. Although comparisons between conditions were adjusted statistically using speed as a covariate, the ideal would be to have actual speed constant in each condition. However, we aimed to examine the participants under ecologically valid conditions, running over ground at self-selected pace in novel footwear and wished to avoid imposing a constraint on self-selected running. Instead, we simply provided consistent instructions to adopt the same comfortable speed that had been used in the 30-minute habituation run. Future studies could attempt to confirm our key findings by imposing a fixed average speed for each participant across all conditions or by fixing speed on an instrumented treadmill. Furthermore, the average running speeds in this study were considerably lower than those of previous studies that have tended to be in excess of $4 m\cdot s^{-1}$. It is not known if the differences we observed would remain at higher running speeds. Future studies could investigate kinematic and spatiotemporal differences between barefoot, minimalist and maximalist shoe conditions across a range of speeds to examine this. Another factor to consider is the 24-hour window between testing sessions. It is possible that participants might have suffered from muscle soreness from running barefoot. However, no participant reported discomfort and any soreness effects should have been mitigated by the counterbalancing of the order of conditions.

The results of this study suggest that both stride length and peak knee flexion moment increase from barefoot to minimalist to maximalist shoes. The lower knee loads in the barefoot and minimalist conditions compared to the maximalist shoe can be explained by a shift in load from the knee to the ankle joint. Recommendations for runners with knee injury to avoid maximalist shoes and choose a minimalist design should, however, be made with caution. Any transition to minimal footwear should be gradual, ideally in conjunction with gait retraining to condition the lower leg structures to the increased demands resulting from the shift in loading. The potential for an offset of the reduced knee load per step with increased number of loading cycles in minimalist shoes should also be considered.

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Table 1: Mean ± SE of kinematic and kinetic outcomes and 95% confidence intervals for pairwise comparisons.

Outcome	Barefoot (BF)	Minimalist (MS)	Maximalist (MX)	BF to MS	MS to MX	BF to MX
Stride length (m)	1.85±0.01	1.91±0.01	1.95±0.01	-0.08 to -0.02	-0.07 to -0.02	-0.12 to -0.06
Peak knee flexion moment ($Nm\cdot kg^{-1}$)	2.51±0.06	2.67±0.06	2.81±0.06	-0.30 to -0.02	-0.28 to -0.01	-0.5 to -0.14
Peak dorsiflexion moment ($Nm\cdot kg^{-1}$)	2.57 ±0.04	2.66±0.03	2.34±0.04	-0.02 to 0.19	-0.42 to -0.22	-0.35 to -0.11

Figure 1. Minimalist and maximalist footwear. Left: minimalist VivoBarefoot® stealth II. Right: maximalist Hoka One One Clifton 2.

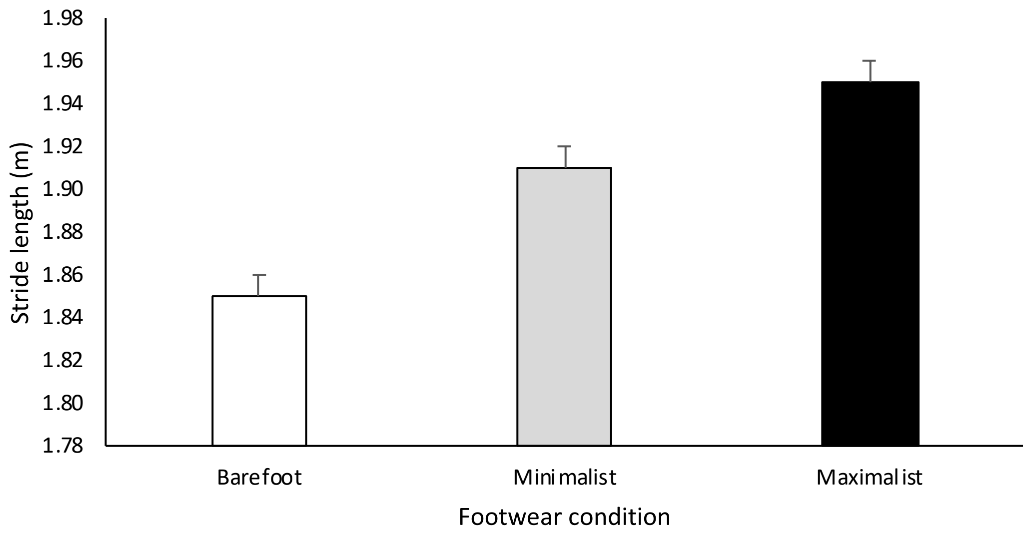

Figure 2. Stride length of 15 recreational runners during running over ground on an indoor runway while barefoot, in minimalist and in maximalist shoes. Columns and error bars are mean and standard error expressed at a common speed of 2.59 m·s^{-1}.

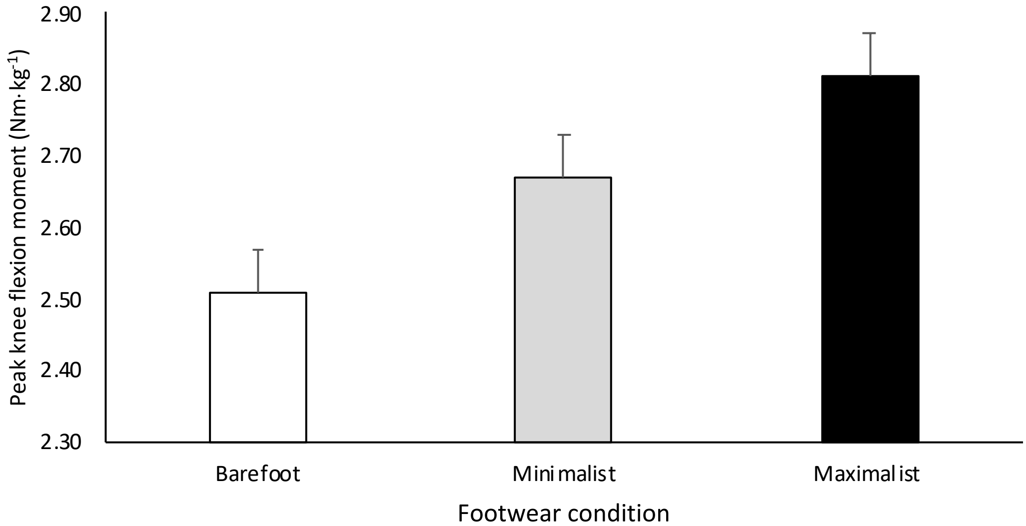

Figure 3. Peak knee flexion moment of 15 recreational runners during running over ground on an indoor runway while barefoot, in minimalist and in maximalist shoes. Columns and error bars are mean and standard error expressed at a common speed of 2.59 $m \cdot s^{-1}$.

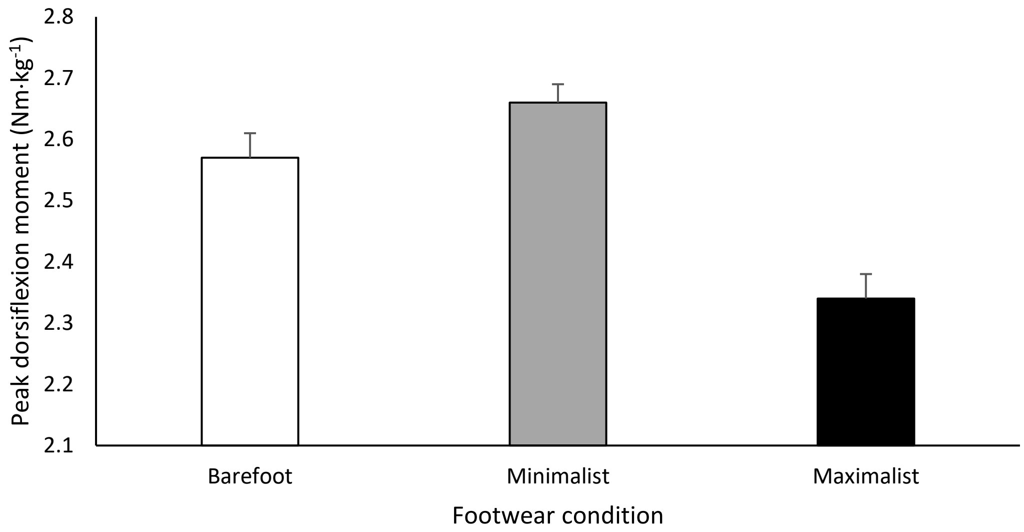

Figure 4. Peak dorsiflexion moment of 15 recreational runners during running over ground on an indoor runway while barefoot, in minimalist and in maximalist shoes. Columns and error bars are mean and standard error expressed at a common speed of 2.59 $m \cdot s^{-1}$.