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Effect of minimalist and maximalist shoes on impact loading and footstrike pattern in habitual rearfoot strike trail runners: an in-field study

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Abstract

Running-related injuries among trail runners are very common and footwear selection may modulate the injury risk. However, most previous studies were conducted in a laboratory environment. The objective of this study was to examine the effects of two contrasting footwear design, minimalist (MIN) and maximalist shoes (MAX), on the running biomechanics of trail runners during running on a natural trail. Eighteen habitual rearfoot strike trail runners completed level, uphill and downhill running at their preferred speeds in both shod conditions. Peak tibial acceleration, strike index and footstrike pattern were compared between the two footwear and slopes. Interactions of footwear and slope were not detected for all the selected variables. There was no significant effect from footwear (F=1.23, *p*=0.27) and slope (F=2.49, *p*=0.09) on peak tibial acceleration and there was no footwear effect on strike index (F=3.82, *p*=0.056). A significant main effect of slope on strike index (F=13.24, *p*<0.001) was found. Strike index during uphill running was significantly greater (i.e., landing with a more anterior foot strike) when compared with level (*p*<0.001, Cohen's *d*=1.72) or downhill running (*p*<0.001, Cohen's *d*=1.44) in either MIN or MAX. The majority

of habitual rearfoot strike runners switched to midfoot strike during uphill running while maintaining a rearfoot strike pattern during level or downhill running. In summary, wearing either one of the two contrasting footwear (MIN or MAX) demonstrated no effect on impact loading and footstrike pattern in habitual rearfoot strike trail runners running on a natural trail with different slopes.

Keywords: downhill running; uphill running; peak tibial acceleration; landing pattern; footwear

Introduction

Impact loading has been extensively investigated because of its potential association with running-related injuries (Chan et al., 2018b; Davis & Futrell, 2016). Impact loading is usually quantified using ground reaction force metrics (i.e., instantaneous and average vertical loading rates). However, the ground reaction force metrics were recently reported not to be strongly associated with tibial bone load, regardless of speeds and slopes (Matijevich et al., 2019). Peak tibial acceleration (PTA), which was the maximum positive vertical tibial acceleration during the early stance phase (Zhang et al., 2016), was strongly correlated to the vertical loading rates (Zhang et al., 2016). PTA was therefore commonly used as a surrogate indicator to quantify impact loading during running (Gruber et al., 2014), particularly in-field running study (Giandolini et al., 2016), in which PTA can be easily measured using a single lightweight inertial sensor.

Footstrike pattern is another factor related to running-related injuries (Baquet et al., 2020; Cheung & Davis, 2011). Footstrike patterns can be classified as rearfoot, midfoot and forefoot strikes, using strike index or footstrike angle. In a recent case study (Baquet et al., 2020), a runner with recurrent calf strain who habitually adopted forefoot strike landing, reported improvement in both symptoms and functions after converting to rearfoot strike; in another study (Cheung & Davis, 2011), three habitual rearfoot strikers relieved their chronic patellofemoral pain after switching to forefoot strike. In addition, footstrike pattern can influence impact-related parameters (Gruber et al., 2014; Knorz et al., 2017). For instance, habitual rearfoot strikers displayed greater PTA when compared with habitual forefoot strikers (Gruber et al., 2014).

Footwear selection was considered a potential way to mitigate the injury risk because it may lower impact loading and modify footstrike pattern. Minimalist (MIN) and maximalist shoes (MAX) are two extreme shoe models commonly available on the market. MIN feature low heel-toe drop and stack height, light mass, lack of arch support and motion control devices (Esculier et al., 2015). MAX and MIN share a few specifications such as low heel-toe drop, however, unlike MIN, MAX have a distinctive feature of highly cushioned midsole.

Despite extensive efforts directed towards understanding how MIN or MAX affect running biomechanics, studies comparing the two shoe models are limited. MIN, when compared with MAX, induced greater loading rates during running (Agresta et al., 2018; Sinclair et al., 2015; 2016a). Sinclair et al. (2016a) also reported greater PTA in MIN than MAX. All these findings indicate that MIN may place runners at higher injury risk than MAX. However, Sinclair (2017) reported that PTA was lower in MIN when compared to that of MAX. Peak patellofemoral force and patellofemoral force per mile were also found to be smaller in MIN than MAX (Sinclair et al., 2016b). MIN also facilitated a more non-rearfoot strike when compared with conventional running shoes (Horvais & Samozino, 2013; Zhang et al., 2017), whereas MAX resulted in a more pronounced rearfoot strike (Borgia & Becker, 2019). Both MIN and MAX may lower impact loading; however, their effects on footstrike pattern appear to be contrasting. To date, debate continues about which footwear type, footstrike pattern or a combination of the two factors is the best for lowering impact loading (Agresta et al., 2018).

Slope (i.e., downhill or uphill running) also influences impact loading and footstrike pattern. A few past studies (Giandolini et al., 2015; Gottschall & Kram, 2005) have suggested that impact loading during downhill running was greater than level or uphill running; rearfoot strike was commonly adopted during downhill running, while midfoot or forefoot strike during uphill running (Lussiana Fabre et al., 2013; Vernillo et al., 2017). Further, the effect of slope on impact loading was different when running in different shod conditions. Vertical loading rates were greater during downhill running than level or uphill running in conventional running shoes, and there were no differences in barefoot condition (An et al., 2015); an interaction effect of footwear and slope was detected on vertical loading rates (Chan et al., 2018a). However, most of these studies were conducted on a treadmill, and biomechanical differences of MIN and MAX were not compared during running on different in-field slopes.

As an emerging sport worldwide, trail running has attracted a large number of participants (Hespanhol Junior et al., 2017). In Europe, the trail running events registered by the International Trail-Running Association (ITRA) were only one in 2003 and dramatically increased to 1,612 in 2015 (data from https://itra.run/); in Hong Kong, trail running events increased from 10 in 2008 to 64 in 2015 (Asia Trail Magazine, 2015). Trail running, according to ITRA, takes place on various natural terrain (i.e., mountain) while minimizing running on paved surfaces (<20% of the total distance). The usual trail running distance ranges from 20 km to more than 300 km with elevation (negative and positive) from 500 m to more than 20,000 m (Easthope, et al., 2010; Giandolini et al., 2016). Like road runners, trail runners also suffered from a high injury risk, i.e., 10.7 injuries per 1,000 hours of running (Hespanhol Junior et al., 2017). Nevertheless, the majority of previous running studies consider only road runners. Unlike road runners, trail runners are usually exposed on unpaved surfaces for more than 15.0 km/week (Hespanhol Junior et al., 2017), and exhibit different running biomechanics (Bean, 2018). To date, it remains largely unknown how MIN and MAX affect trail runners in impact loading and footstrike pattern.

Shoe property (i.e., heel-toe drop) was reported to result in different biomechanical effects during overground and treadmill running (Chambon et al., 2015), and field research would allow greater generalizability to natural contexts and higher external validity (Aziz, 2017). Therefore, the objective of this study was to investigate the characteristics of impact loading and footstrike pattern of habitual rearfoot strike trail runners during running on a natural trail in either MIN or MAX and to compare their differences during downhill, level and uphill running. It was hypothesized that trail runners would experience greater impact loading and would land with a more anterior foot strike during downhill running in MIN when compared with MAX. It was also hypothesized that impact loading would be greater during downhill running than level or uphill running, and rearfoot strike would be adopted during downhill running and non-rearfoot strike during uphill running.

Methods

Healthy regular trail runners were recruited from local running clubs or subjects currently participating in our other running projects. The runners were included if they were between 20 and 55 years; their minimum weekly trail running mileage was 10 km during the past 12 months; and they had no experience with the test shoe models (Newton Running Lab™, MV2, Boulder, CO, USA; Hoka One One™, Clifton 3, Goleta, CA, USA). The runners were excluded if they had any active musculoskeletal injuries in the past six months, or any known diseases that might affect gait.

According to a previous study (Altman & Davis, 2012), only 77% runners could accurately report their footstrike patterns, a screening test was therefore conducted to exclude non-rearfoot strikers. Footstrike angle has been widely used as an alternative of strike index for determining footstrike pattern (Altman & Davis, 2012). As those runners from our other running projects had been determined by footstrike angle, the same method was therefore used in the screening test. Considering that symmetric running gait was largely reported (Karamanidis et al., 2003), only the dominant limb, defined as the leg to kick a ball (van Melick et al., 2017), was evaluated. The runners were instructed to run for 10 minutes in their own shoes at their preferred speeds on an instrumented treadmill (Advance Mechanical Technology Inc., MA, USA). The slope of the treadmill was set at 0°. Two markers were attached at the heel and 2nd metatarsal head of the dominant foot and their trajectories were captured at 200 Hz using a motion capture system (Vicon Nexus, Oxford, UK) for 30 seconds at the beginning, middle and end of the run. Footstrike angle was calculated as the angle of the foot with respect to the ground in the sagittal plane at initial contact, which was determined when vertical ground reaction force exceeded 10 N (Chan et al., 2018a). The runner who exhibited more than 90% of footfalls with footstrike angles greater than 8° (Altman & Davis, 2012) was eventually enrolled in this study. Finally, 18 runners (9 females, 9 males) were recruited. Their mean (standard deviation) of age, body mass and height were 38.5 (9.6) years, 58.4 (8.2) kg and 1.66 (0.09) m, respectively. Their minimum weekly trail running mileage and trailing running experience were 28.4 (22.2) km and 6.1 (7.7) years, respectively. The experimental procedures were reviewed and approved by concerning institutional review board and written consent was obtained from each runner prior to the test.

The two shoe models were selected because both were reported to affect running biomechanics (Chan et al., 2018a; Zhang et al., 2017). The shoes were rated from five aspects (weight, stack height, heel-toe drop, motion control and stability technologies, and flexibility) using the minimalist index rating scale proposed by Esculier et al. (2015). The minimalist index score is 32% for the Newton™ shoe model, which was defined as MIN, and 80% for the Hoka™ shoe model, which was classified as MAX (Table 1).

All runners performed an in-field running test in both MIN and MAX. The test consisted of three sessions (level, uphill, downhill) and was conducted at the Eagle's Nest Nature Trail (Kowloon, Hong Kong). Level running was performed on a flat 75-m trail. Uphill and downhill running were completed in a 50-m sloped trail, with irregular gradient between 8° and 26° (mean slope of 15°) and altitude difference of 10 m.

The runners were asked to avoid any vigorous exercises 24 hours prior to the test.

Before data collection, they had 10 minutes to familiarize with the trail and shoe models and determine their preferred paces. The runners ran on each slope for five trials using the pace similar to their regular trail running. The average pace over the five trials was considered the preferred pace of the individual subject. During the test, a tri-axial accelerometer (IMeasureU, Auckland, New Zealand) was firmly affixed at the distal anteromedial tibia of the dominant leg with vertical axis aligning with the tibia. Though the non-dominant side was not analyzed, a pair of size-matched pressure sensing insoles (Pedar-X, Novel, Munich, Germany) were integrated in both shoes and trajectories of the center of pressure were measured step-by-step. The Pedar insoles feature low thickness (1.9 mm) and light weight (the whole Pedar-X system is 360 grams), which was expected to minimally affect the shoe characteristics. Acceleration data were sampled at 1,000 Hz, and pressure data were sampled at 100 Hz. For the same condition, data from three successful trials (i.e., within 5% from the determined preferred pace) were recorded. All subjects completed the three sessions in both shoe models in a randomized order and had a minimum of 30-minutes' rest between sessions.

Data of the acceleration and deceleration phases (i.e., first and last 15% of each trial) were excluded from analyses. Accelerometer data were filtered at 50 Hz using a fourth order, low-pass Butterworth filter (Zhang et al., 2016). PTA was extracted to quantify impact loading. Strike index was defined as the location of the center of pressure at initial contact along the long axis of the foot and was described in percentage of the foot length (Cavanagh

& Lafortune, 1980). A strike index of 0–33% indicates rearfoot strike pattern, 34–67% midfoot strike pattern, and 68–100% forefoot strike pattern (Cavanagh & Lafortune, 1980). Data were averaged across all footfalls to obtain an averaged PTA and strike index for each running condition. Footstrike pattern was determined for each running condition using strike index.

All statistical tests were performed using SPSS software (v25.0, SPSS Inc., Chicago, USA). One-way (3 slopes) repeated measures analysis of variance (ANOVA) was conducted to examine differences in running speed. If indicated, two-way (2 footwear models × 3 slopes) repeated measures ANOVA was performed to examine differences in PTA and strike index with speed as a co-variate due to its association with PTA (Sheerin et al., 2018). If main effects were detected, post-hoc comparisons were performed on the basis of the least significant difference criterion. Significance level was set at 0.05. Cohen's *d* or partial eta square (η_p^2) were reported for quantifying the magnitude of group difference. With regard to footstrike pattern, Friedman ranks test was employed to compare the distributional characteristics among conditions. If indicated, Wilcoxon signed ranks tests were adopted to determine differences between groups.

Results

Speeds during level, uphill and downhill running were 3.2 (0.6), 2.6 (0.5) and 3.3 (0.6) m/s, respectively and there were significant differences across all slopes (F=58.3, p<0.001, η_p^2 =0.77). Speed was significantly faster during level (p<0.001, Cohen's d=1.17) and downhill running (p<0.001, Cohen's d=1.39) in comparison to uphill running. There were no significant differences in the running speed between level and downhill running (p=0.16, Cohen's d=0.24).

Values of PTA and strike index and statistical analyses were summarized in Table 2 and Figure 1. Speed significantly affected PTA (F=44.12, p<0.001, η_p^2=0.47). After controlling the speed effect, there were no footwear-by-slope interaction (F=0.14, p=0.87), footwear (F=1.23, p=0.27) and slope effects (F=2.49, p=0.09) on PTA. Strike index was not affected by speed (F=0.85, p=0.36). There was no footwear-by-slope interaction (F=1.49, p=0.24) and footwear effect (F=3.82, p=0.056) on strike index. There was a main effect for slope in the strike index (F=13.24, p<0.001, η_p^2=0.35). Strike index during uphill running was significantly larger (i.e., landing with a more anterior foot strike) than that during level (p<0.001, Cohen's d=1.72) or downhill running (p<0.001, Cohen's d=1.44). Strike index was not different between level and downhill running (p=0.42, Cohen's d=0.26).

Regarding the distribution of footstrike pattern (Figure 2), there were no statistical differences between MIN and MAX regardless of slopes (p>0.32). However, significant differences were found across all slopes during running in either MIN (χ^2=20.67, p<0.001) or

MAX (χ^2=18.73, p<0.001). When running in MIN, the proportion of midfoot and forefoot strike pattern during uphill running were significantly more than that during level (p=0.002) or downhill running (p=0.005). Similar observations were noted between uphill and level (p=0.001) or downhill running (p=0.002) in MAX. There were no differences between level and downhill running in either MIN (p=0.16) or MAX (p=0.16).

Discussion

This study investigated the effects of MIN and MAX on PTA and footstrike pattern in habitual rearfoot strike trail runners during running on a natural trail. In contrast to our original hypotheses, we did not observe any footwear effects on PTA, strike index and footstrike pattern regardless of slope. There were no significant differences in PTA across all slopes. Nevertheless, a greater strike index was found during uphill when compared to that of level or downhill running, and most of the trail runners switched to midfoot strike during uphill running while maintaining rearfoot strike during level and downhill running.

There were no significant differences in the PTA and strike index between MIN and MAX, suggesting that footwear does not immediately affect impact loading and footstrike pattern of habitual rearfoot strike trail runners when running with different slopes on a natural trail. To confirm such non-significant differences, post-hoc power calculation has been conducted (PTA: η_p^2=0.02, p=0.27, power: 83.0%; Strike index: η_p^2=0.07, p=0.056, power: 98.0%). The Type II errors were found to be within a threshold of 20%, which supports the observation that there were no significant effects from the types of footwear on both impact loading and footstrike pattern. However, our findings were inconsistent to that reported by Sinclair et al. (2016a) and Sinclair (2017). Sinclair et al. (2016a) observed significantly greater PTA in MIN when compared with conventional shoes and MAX, whereas Sinclair (2017) reported lower PTA in MIN. Both studies observed plantarflexion at the ankle joint during footstrike in MIN when compared to the other two footwear models, indicating a non-rearfoot strike pattern in MIN. Such discrepancy could be explained by different running surfaces. Our study was conducted on a natural trail. This unpaved trail features uneven surface and irregular gradients, which are quite different from the indoor runway (i.e., smooth and artificial surface) in their studies. The soil surface in our study and the 6-mm Altro sports floor (Altro Ltd.) in the aforementioned two studies had different stiffness, which would elicit different leg stiffness, ground reaction force and running postures (Bean, 2018; Schütte et al., 2016). Different runner population (trail runners in our study; road runners in the two aforementioned studies) may also contribute to the inconsistent findings because trail runners exhibited significantly smaller footstrike angle and lower ankle stiffness than road runners (Bean, 2018).

The results of this study were also different from another study conducted on treadmill

(Ogston, 2019), in which plantar loading was compared between MIN and MAX, a greater plantar loading was observed in MIN when compared to that of MAX. This might be because the running test was conducted on a natural trail in our study while it was conducted on a treadmill in that specific study (Ogston, 2019). The mechanics were not therefore fully comparable between overground and treadmill running and shoe effects on vertical loading rates were different during overground and treadmill running (Chambon et al., 2015). Finally, all trail runners did not have any experience in either styles of shoes (MIN or MAX) in our study, whereas the subjects had previous experience of wearing MIN in those previous studies (Sinclair et al. (2016a) and Sinclair (2017)) and the runners habitually wore maximal cushioned shoes in the study by Ogston (2019).

An et al. (2015) found that vertical loading rates were greater during downhill running in comparison to level or uphill running. Similarly, some other studies also reported greater values of the impact-related parameters (i.e., impact peak) during downhill running when compared to level or uphill running (Gottschall & Kram, 2005; Mizrahi et al., 2000). Further, Chan et al. (2018a) observed greater vertical loading rates during downhill running when compared with level running on treadmill regardless of shoes. It appears that loading impact during downhill running would be larger than that during level or uphill running. However, our study found no differences in PTA across all slopes in either MIN or MAX after eliminating speed effect. Such unexpected results could be explained from the following four aspects. Firstly, the aforementioned four studies were conducted on treadmill, whereas our study was conducted on a natural trail. We cannot rule out the fact that the two running surfaces were different (i.e., stiffness, smoothness). Besides, the constant slopes adopted in those studies, i.e., 10° by An et al. (2015); 3°, 6° and 9° by Gottschall and Kram (2005); 4° by Mizrahi et al. (2000); and 5.7° by Chan et al. (2018a), were less than that of the natural trail, which has an irregular slope (8°~26°) in our study. Furthermore, conventional running shoes were adopted in their studies, while MIN and MAX were used in our study. It was reported that footwear and slope interacted on vertical loading rates (Chan et al., 2018a). Lastly, biomechanical differences (Bean, 2018) between road runners in the four aforementioned studies and trail runners in our study may also contribute to the inconsistent results.

Footstrike pattern was found to be affected by slope (Vernillo et al., 2017). It was expected that more anterior footstrike (i.e., midfoot or forefoot strike) would be observed during uphill running and more rearfoot strike during downhill running. In our study, the habitual rearfoot strike trail runners landed with a more anterior foot strike (i.e., a greater strike index) during uphill than level or downhill running. Comparing the distribution of footstrike patterns, more than half of the trail runners (MIN: 50%; MAX: 55.6%) switched to midfoot strike during uphill running while maintaining their habitual rearfoot strike pattern during level and downhill running. During uphill running, trial runners were found to run with a midfoot strike and demonstrated a more anterior footstrike pattern as speed increasing. Our findings were in corroboration with the results of the study of Gottschall and Kram (2005), in which they reported a transition from rearfoot strike during level or downhill running to a mixed footstrike pattern during uphill running. However, An et al. (2015) observed that half of their subjects exhibited a mixed footstrike pattern during level or downhill running. This might be due to runners with different running pattern being recruited. Both rearfoot and non-rearfoot strikers were recruited by An et al. (2015), whereas only rearfoot strikers were included in our study and the study by Gottschall and Kram (2015).

In addition, large inter-individual variability was observed for both PTA and strike index (Figure 1). The erratic terrain of the natural trail may contribute to such great variation. Optimal running form requires a precise interplay of lower-limb joint mobility and stability, which becomes more complex during running on a natural trail. Unlike running on treadmill or paved road, when running on natural trail, trail runners may require greater lower-limb joint integrity alongside greater kinematic variability (Schütte et al., 2016) to maintain dynamic stability during dealing with the irregular surface and variant slopes. Withstanding this point, each trail runner may develop individual strategy. In a case study, for example, Giandolini et al. (2015) demonstrated an atypical footstrike profile of the trail runner during a trail running race. Further studies are required to investigate such interpolation.

Several limitations should be highlighted. Firstly, in this in-field study, impact loading was quantified using PTA. However, measurement of PTA using a skin-mounted accelerometer, was reported to be moderately associated with key ground reaction force parameters, i.e. vertical loading rates (Greenhalgh et al., 2012). Secondly, though the running was performed in a natural trail, runner's habitual footstrike pattern was determined during treadmill running, which may not be the same during in-field running. Moreover, footstrike pattern of only dominant limb was evaluated. Larson et al. (2011) found that 5.9% of 936 road runners displayed split strikes that rearfoot strike on one side and non-rearfoot strike on the other side. It would be more informative if both sides were evaluated. Thirdly, data were collected from a relatively short distance of the natural trail, which may not fully represent the performance of the runner during the entire trail. In future, data should be collected throughout the entire trail to explore the interaction of footwear and slope on running biomechanics of trail runners. Furthermore, our study only included MIN and MAX, which led to our findings being incomparable with previous studies because of lacking a reference (i.e., conventional running shoes). Lastly, the adaptation period (10 minutes) might not be long enough to allow the runners fully familiarizing with the novel shoes.

In conclusion, the effects of minimalist and maximalist footwear on impact loading and footstrike pattern were investigated during running on a natural trail in a group of trail runners who habitually landed with a rearfoot strike pattern. Wearing either one of the two contrasting types of footwear (MIN or MAX), the habitual rearfoot trail runners were found to switch to a midfoot strike pattern during uphill running while maintaining a rearfoot strike pattern during level or downhill running. Type of footwear did not immediately affect impact loading and footstrike pattern regardless of slope. The current findings demonstrated that minimalist and maximalist shoes have minimal effects on the running biomechanics of trail runners when running on a natural trail with irregular surfaces and variant slopes.

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Declaration of interest

None.

References

Agresta, C., Kessler, S., Southern, E., Goulet, G. C. Zernicke, R., & Zendler, J. D. (2018). Immediate and short-term adaptations to maximalist and minimalist running shoes. *Footwear Science, 10*(2), 95-107. doi: 10.1080/19424280.2018.1460624.

Altman, A. R., & Davis, I. S. (2012). A kinematic method for footstrike pattern detection in barefoot and shod runners. *Gait & Posture, 35*(2), 298-300. doi: 10.1016/j.gaitpost.2011.09.104.

An, W., Rainbow, M. J., & Cheung, R. T. H. (2015). Effects of surface inclination on the vertical loading rates and landing pattern during the first attempt of barefoot running in habitual shod runners. *BioMed Research International, 2015*, 240153. doi: 10.1155/2015/240153.

Asia Trail Magazine (2015). http://asiatrailmag.com/race-calendar/

Aziz, H. (2017). Comparison between field research and controlled laboratory research. *Archives of Clinical and Biomedical Research, 1*, 101–104. doi: 10.26502/acbr.50170011.

Baquet, A., Mazzone, B., Yoder, A., & Farrokhi, S. (2020). Conversion to a rearfoot strike pattern during running for prevention of recurrent calf strains: a case report. *Physical Therapy in Sport, 41*, 64-70. doi: 10.1016/j.ptsp.2019.11.004.

Bean, R. C. R. (2018). Trail runners: neuromuscular and biomechanical insights. PhD Thesis. University of Cape Town.

Borgia, B., & Becker, J. (2019). Lower extremity stiffness when running in minimalist, traditional, and ultra-cushioning shoes. *Footwear Science, 11*(1), 45-54. doi: 10.1080/19424280.2018.1555860.

Cavanagh, P. R., & Lafortune, M. A. (1980). Ground reaction forces in distance running.

Journal of Biomechanics, 13(5), 397-406. doi: 10.1016/0021-9290(80)90033-0.

Chambon, N., Delattre, N., Guéguen, N., Berton, E., & Rao, G. (2015). Shoe drop has opposite influence on running pattern when running overground or on a treadmill. *European Journal of Applied Physiology, 115*(5), 911-918. doi: 10.1007/s00421-014-3072-x.

Chan, Z. Y. S., Au, I. P. H., Lau, F. O. Y., Ching, E. C. K., Zhang, J. H., & Cheung, R. T. H. (2018a). Does maximalist footwear lower impact loading during level ground and downhill running? *European Journal of Sport Science, 18*(8), 1083-1089. doi: 10.1080/17461391.2018.1472298.

Chan, Z. Y. S., Zhang, J. H., Au, I. P. H., An, W. W., Shum, G. L. K., Ng, G. Y. F., & Cheung, R. T. H. (2018b). Gait retraining for the reduction of injury occurrence in novice distance runners: 1-year follow-up of a randomized controlled trail. *The American Journal of Sports Medicine, 46*(2), 388-395. doi: 10.1177/0363546517736277.

Cheung, R. T., & Davis, I. S. (2011). Landing pattern modification to improve patellofemoral pain in runners: a case series. *Journal of Orthopaedic & Sports Physical Therapy, 41*(12), 914-919. doi: 10.2519/jospt.2011.3771.

Davis, I. S., & Futrell, E. (2016). Gait retraining, altering the fingerprint to gait. *Physical Medicine and Rehabilitation Clinics of North America, 27*(1), 339-355. doi: 10.1016/j.pmr.2015.09.002.

Easthope, C. S., Hausswirth, C., Louis, J., Lepers, R., Vercruyssen, F., & Brisswalter, J. (2010). Effects of a trail running competition on muscular performance and efficiency in well-trained young and master athletes. *European Journal of Applied Physiology, 110*(6), 1107-1116. doi: 10.1007/s00421-010-1597-1.

Esculier, J. F., Dubois, B., Dionne, C. E., Leblond, J., & Roy, J. S. (2015). A consensus definition and rating scale for minimalist shoes. *Journal of Foot and Ankle Research, 8*(1), 42. doi: 10.1186/s13047-015-0094-5.

Giandolini, M., Pavailler, S., Samozino, P., Morin, J. B., & Horvais, N. (2015). Foot strike pattern and impact continuous measurements during a trail running race: proof of concept in a world-class athlete. *Footwear Science*, *7*(2), 127-137. doi: 10.1080/19424280.2015.1026944.

Giandolini, M., Horvais, N., Rossi, J., Millet, G. Y., Samozino, P., & Morin, J. B. (2016). Foot strike pattern differently affects the axial and transverse components of shock acceleration and attenuation in downhill trail running. *Journal of Biomechanics, 49*(9), 1765-1771. doi: 10.1016/j.jbiomech.2016.04.001.

Gottschall, J. S., & Kram, R. (2005). Ground reaction forces during downhill and uphill running. *Journal of Biomechanics, 38*(3), 445-452. doi 10.1016/j.jbiomech.2004.04.023.

Greenhalgh, A., Sinclair, J., Protheroe, L., & Chockalingam, N. (2012). Predicting impact shock magnitude: which ground reaction force variable should we use. *International*

Journal of Sports Science and Engineering, 6(4), 225-231.

Gruber, A. H., Boyer, K. A., Derrick, T. R., & Hamill, J. (2014). Impact shock frequency components and attenuation in rearfoot and forefoot running. *Journal of Sport and Health Science*, *3*(2), 113-121. doi: 10.1016/j.jshs.2014.03.004.

Hespanhol Junior, L. C., Van Mechelen, W., & Verhagen, E. (2017). Health and economic burden of running-related injuries in Dutch trailrunners: a prospective cohort study. *Sports Medicine, 47*(2), 367-377. doi: 10.1007/s40279-016-0551-8.

Horvais, N., & Samozino, P. (2013). Effect of midsole geometry on foot-strike pattern and running kinematics. *Footwear Science, 5*(2), 81-89. doi: 10.1080/19424280.2013.767863.

Karamanidis, K., Arampatzis, A., & Brüggemann, G. P. (2003). Symmetry and reproducibility of kinematic parameters during various running techniques. *Medicine & Science in Sports & Exercise, 35*(6), 1009-1016. doi: 10.1249/01.MSS.0000069337.49567.F0.

Knorz, S., Kluge, F., Gelse, K., Schulz-Drost, S., Hotfiel, T., Lochmann, M., ... Krinner, S. (2017). Three-dimensional bio- mechanical analysis of rearfoot and forefoot running. *Orthopaedic Journal of Sports Medicine, 5*(7), 1–10. doi:10. 1177/2325967117719065.

Larson, P., Higgins, E., Kaminski, J., Decker, T., Preble, J., Lyons, D., McIntyre, K., & Normile, A. (2011). Foot strike patterns of recreational and sub-elite runners in a long-distance road race. *Journal of Sports Sciences, 29*(15), 1665-1673. doi:

10.1080/02640414.2011.610347.

Lussiana, T., Fabre, N., Hébert-Losier, K., & Mourot, L. (2013). Effect of slope and footwear on running economy and kinematics. *Scandinavian Journal of Medicine & Science in Sports*, *23*(4), e246-e253. doi: 10.1111/sms.12057.

Matijevich, E. S., Branscombe, L. M., Scott, L. R., & Zelik, K. E. (2019). Ground reaction force metrics are not strongly correlated with tibial bone load when running across speeds and slopes: implications for science, sport and wearable tech. *PLoS ONE, 14*(1), e0210000. doi: 10.1371/journal. pone.0210000

Mizrahi, J., Verbitsky, O., & Isakov, E. (2000). Shock accelerations and attenuation in downhill and level running. *Clinical Biomechanics, 15*(1), 15-20. doi: 10.1016/s0268-0033(99)00033-9.

Ogston, J. K. (2019). Comparison of in-shoe plantar loading forces between minimalist and maximalist cushion running shoes. *Footwear Science, 11*(1), 55-61. doi: 10.1080/19424280.2018.1561760.

Pedar®-X. http://www.syna-med.com.tw/pdf/pedarX_eng.pdf

Schütte, K. H., Aeles, J., De Beéck, T. O., van der Zwaard, B. C., Venter, R., & Vanwanseele, B. (2016). Surface effects on dynamic stability and loading during outdoor running using wireless trunk accelerometry. *Gait & Posture, 48*, 220-225. doi: 10.1016/j.gaitpost.2016.05.017.

Sinclair, J., Richards, J., & Shore, H. (2015). Effects of minimalist and maximalist footwear on Achilles tendon load in recreational runners. *Comparative Exercise Physiology, 11*(4), 239-244.

Sinclair, J., Fau-Goodwin, J., Richards, J., & Shore, H. (2016a). The influence of minimalist and maximalist footwear on the kinetics and kinematics of running. *Footwear Science, 8*(1), 33-39. doi: 10.1080/19424280.2016.1142003.

Sinclair, J., Richards, J., Selfe, J., Fau-Goodwin, J., & Shore, H. (2016b). The influence of minimalist and maximalist footwear on patellofemoral kinetics during running. *Journal of Applied Biomechanics, 32*(4), 359-364. doi: 10.1123/jab.2015-0249.

Sinclair, J. (2017). The influence of minimalist, maximalist and conventional footwear on impact shock attenuation during running. *Movement & Sports Sciences, 95*, 59-64. doi: 10.1051/sm/2016010.

van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G., van Cingel, R. E. H. (2017). How to determine leg dominance: the agreement between self-reported and observed performance in healthy adults. PLoS One, 12(12), e0189876. doi: 10.1371/journal.pone.0189876

Vernillo, G., Giandolini, M., Edwards, W. B., Morin, J. B., Samozino, P., Horvais, N., & Millet, G. Y. (2017). Biomechanics and physiology of uphill and downhill running. *Sports Medicine, 47*(4), 615-629. doi: 10.1007/s40279-016-0605-y.

Zhang, J. H., An, W. W., Au, I. P. H., Chen, T. L., & Cheung, R. T. H. (2016). Comparison of the correlations between impact loading rates and peak accelerations measured at two different body sites: intra- and inter-subject analysis. *Gait & Posture, 46*, 53-56. doi: 10.1016/j.gaitpost.2016.02.002.

Zhang, J. H., McPhail, A. J. C., An, W. W., Naqvi, W. M., Chan, D. L. H., Au, I. P. H., … Cheung, R. T. H. (2017). A new footwear technology to promote non-heelstrike landing and enhance running performance: fact or fad? *Journal of Sports Sciences, 35*(15), 1533-1537. doi: 10.1080/02640414.2016.1224915.

Figure Captions

Figure 1. Peak tibial acceleration (a) and strike index (b) during level, uphill and downhill running in minimalist and maximalist shoes.

Figure 2. The proportion of rearfoot, midfoot and forefoot strike pattern during level, uphill and downhill running in minimalist and maximalist shoes. *, $p < 0.05$.

Table 1.

Specifications of the maximalist and minimalist shoe models

	Maximalist shoes	Minimalist shoes
Shoe model	Clifton 3, Hoka One One™ (Goleta, CA, USA)	MV2, Newton Running Lab™ (Boulder, CO, USA)
Weight (g)	244	167
Forefoot height (mm)	29.5	18
Heel height (mm)	34.5	17
Heel-toe drop (mm)	5	0
Minimalist index (%) *	32	80
a. Weight	2	4
b. Stack height	1	3
c. Heel-toe drop	3	5
d. Motion control and stability technologies	2	4
e. Flexibility (longitudinal and torsional)	0	4

* the two shoe models (men's size US 9) were rated using the minimalist index proposed by Esculier et al. (2015), and the total score was the sum of all five subscores (a, b, c, d, and e) multiplying by 4.

Table 2.

Comparison of peak tibial acceleration (PTA) and strike index between footwear conditions and slopes. Results are presented in mean ± standard deviation.

	Slope	Maximalist shoes	Minimalist shoes	Repeated measures analysis of variance with speed as covariate				
				Footwear × Slope	Footwear × Speed	Speed	Footwear	Slope
PTA (g)	Level	9.3 ± 2.4	9.3 ± 2.6	F = 0.14, p = 0.87, η_p^2 = 0.01	F = 0.93, p = 0.34, η_p^2 = 0.02	F = 44.12, ***p* < 0.001**, η_p^2 = 0.47	F = 1.23, p = 0.27, η_p^2 = 0.02	F = 2.49, p = 0.09, η_p^2 = 0.09
	Uphill	5.8 ± 2.6	6.0 ± 2.8					
	Downhill	8.5 ± 2.8	8.6 ± 2.6					
Strike index (%)	Level	22.0 ± 6.6	19.1 ± 4.3	F = 1.49, p = 0.24, η_p^2 = 0.06	F = 3.15, p = 0.08, η_p^2 = 0.06	F = 0.85, p = 0.36, η_p^2 = 0.02	F = 3.82, p = 0.056, η_p^2 = 0.07	F = 13.24, ***p* < 0.001**, η_p^2 = 0.35
	Uphill	43.4 ± 16.7	42.9 ± 17.9					
	Downhill	23.3 ± 10.1	23.3 ± 9.6					

Bold, significant difference (p < 0.05).

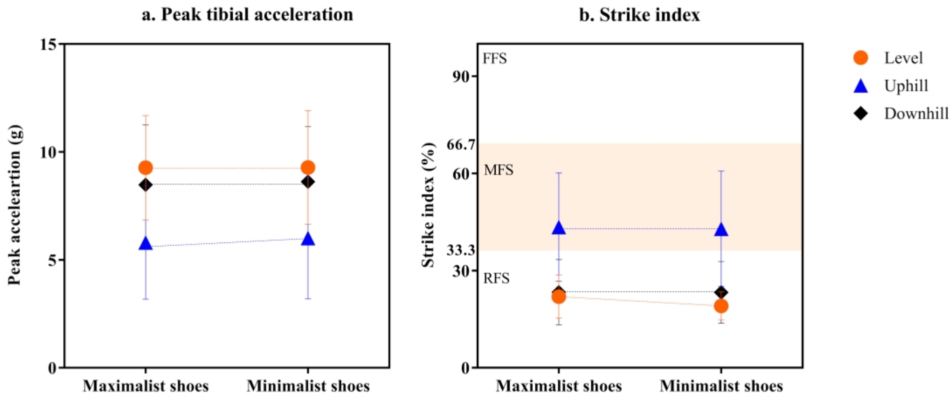

Figure 1. Peak tibial acceleration (a) and strike index (b) during level, uphill and downhill running in minimalist and maximalist shoes.

282x127mm (600 x 600 DPI)

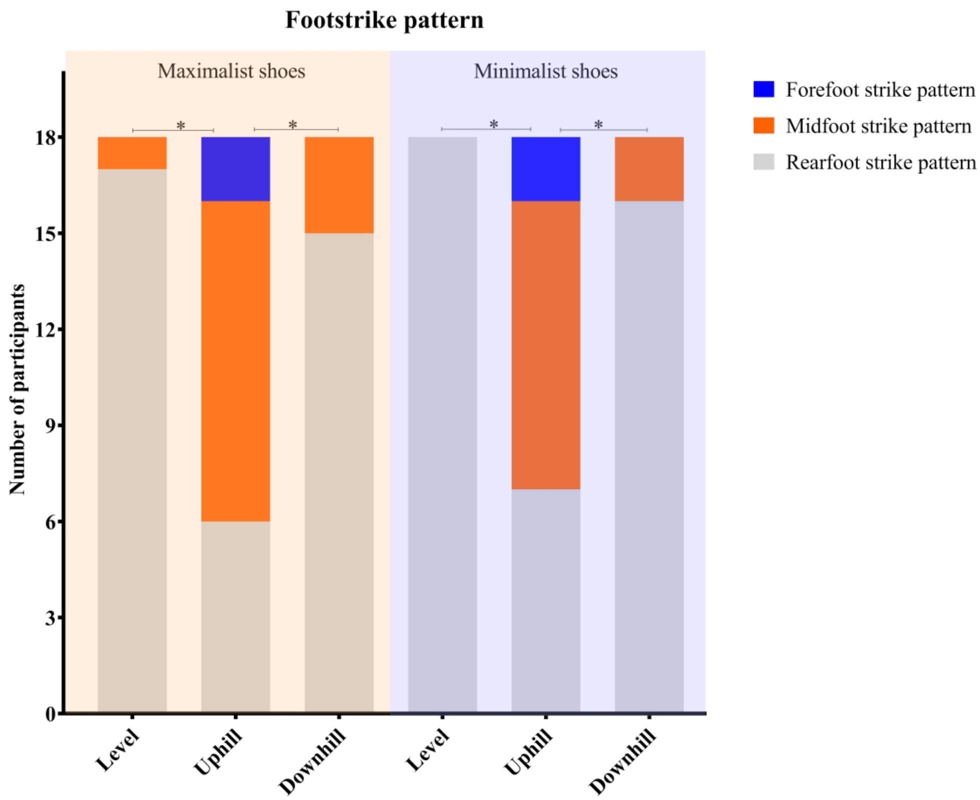

Figure 2. The proportion of rearfoot, midfoot and forefoot strike pattern during level, uphill and downhill running in minimalist and maximalist shoes. *, $p < 0.05$.

262x215mm (600 x 600 DPI)