1 **The influence of minimalist footwear and stride length reduction on lower-extremity running**
2 **mechanics and cumulative loading**

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Abstract

Objectives: To examine the effects of shoe type and stride length reduction on lower-extremity running mechanics and cumulative loading.

Design: Within-subject with four conditions: 1) control shoe at preferred stride length (PSL); 2) control shoe at 90% PSL; 3) minimalist shoe at PSL; 4) minimalist shoe at 90% PSL.

Methods: Fourteen young healthy males ran overground at their preferred speed while motion capture, force platform, and plantar pressure data were collected. Peak moments, impulse, mechanical work, and cumulative impulse were calculated at the metatarsophalangeal (MTP), ankle, and knee joint, and compared between conditions using a 2 x 2 factor repeated measures ANOVA.

Results: In general, running in minimalist footwear increased measures of loading at the MTP joint and ankle joint (mean increases of 7.3% and 5.9% respectively), but decreased measures of loading at the knee (mean decrease of 7.3%). Conversely, running with reduced stride length decreased single-stance measures of loading at the ankle and knee joint (ranging from -0.9% to -20.5%), though cumulative impulse was higher at the ankle and lower at the knee.

Conclusions: Running in minimalist shoes increased loads at the MTP and ankle joint, which may explain some of the incidence of overuse injuries observed in minimalist shoe users. Decreased ankle loads at 90% PSL were not necessarily sufficient to reduce cumulative loads when impulse and loading cycles were weighted equally. Knee loads decreased more when running at 90% PSL (16.2% mean reduction) versus running in a minimalist shoe (7.3% mean reduction), but both load reduction mechanisms appeared to have an additive effect (22.2% mean reduction).

Keywords: inverse dynamics; metatarsophalangeal joint; ankle joint; knee joint; shoes; running injury

Introduction

Minimalist running shoes are defined by their low weight, finite heel cushioning, minimal difference between heel and toe height, limited stabilization mechanisms, and highly flexible sole. In recent years, minimalist shoes have risen in popularity out of the demand for footwear that mimics barefoot running while also providing protection against sharp and dangerous foreign objects. Compared to traditional running shoes, minimalist shoe running has been characterized by a more anterior foot strike pattern^{1,2} and a reduction in stride length,³ however these results have not been reproduced in some studies.⁴ Alterations in foot strike pattern as well as stride length are known to influence lower-extremity joint loading,^{5,6} but the relative influence of stride length reduction in minimalist shoe runners has never been independently nor systematically examined.

The predominant injuries reported in minimalist shoe runners include Achilles tendinopathy, plantar fasciitis, and metatarsal stress fractures.^{7,8} No direct conclusions have been drawn as to whether these injuries are the end result of changes in foot strike pattern, stride length reduction, or some alternative factor. Although a forefoot strike running pattern has been associated with increased ankle joint loading,^{5,9} no studies have examined metatarsophalangeal (MTP) joint mechanics in minimalist shoe running. Similarly, while stride length reductions have been associated with reductions in lower extremity loading,¹⁰ they are associated with an increased number of loading cycles for a given running distance. This is an important distinction because overuse injuries in running are ultimately caused by the accumulation of tissue damage over time, dependent not only on loading magnitude, but the duration of loading and number of loading cycles.^{11,12}

While it is common practice to measure only discrete biomechanical variables associated with a single stance phase of running, previous work has either introduced or incorporated novel methods to account for changes in spatiotemporal parameters, such as duration of loading and number of loading cycles

occurring in different running conditions. Edwards et al.¹³ used a stressed-life approach that accounted for tissue damage, repair, and adaptation, but this approach was highly theoretical and required several different modeling techniques. Miller et al.¹⁴ introduced the concept of per-unit-distance loads, where the angular impulse for a given stance phase was normalized by stance time and stride length to compare different speeds of locomotion (i.e. walking and running). Similarly, Petersen et al.¹⁵ summated knee joint impulses associated with alterations in running speed to quantify a cumulative impulse that accounted for changes in the number of loading cycles for a 1000 m distance. These latter approaches benefit from their relative simplicity and ease of implementation.

The purpose of this study was to examine the influence of minimalist shoes and stride length reduction on lower-extremity mechanics and cumulative loading. To this end we quantified peak moments, angular impulse, mechanical work, and cumulative impulse in the sagittal plane for the MTP, ankle, and knee joints. During testing, participants ran at their preferred 5 km running speed in two shoes (traditional vs. minimalist) and two stride length (preferred stride length and 90% preferred stride length) conditions. It was hypothesized that running in a minimalist shoe would decrease lower-extremity joint loads, and that reductions in loads associated with reduced stride length would outweigh the detrimental increase in the number of loading cycles required to run a given distance.

Methods

Fourteen male recreational runners (26.2 ± 4.2 y; 178.4 ± 5.4 cm; 75.6 ± 5.6 kg) participated in this study. For this 2×2 factor repeated measures design, a sample size of 14 was associated with a minimum detectable effect size of $d = 0.57$ ($\alpha = 0.05$, $\beta = 0.2$). Inclusion criteria required that participants: were 18-35 years, ran at least 10 km/week, had no lower limb injuries in the previous 3 months, displayed a rearfoot strike pattern, and had no prior experience running in minimalist footwear. Females were excluded to eliminate any biomechanical differences associated with sex.¹⁶ Prior to subject recruitment,

ethics approval was obtained from the Conjoint Health Research Ethics Board at the University of Calgary, and participants provided written informed consent.

Participants attended a two-hour data collection session at the University of Calgary's Human Performance Laboratory. Motion capture, force platform, and plantar pressure data were collected as participants ran overground at their preferred running speed for ten trials at each of four conditions: (1) control shoe at preferred stride length (PSL); (2) control shoe at 90% PSL; (3) minimalist shoe at PSL; (4) minimalist shoe at 90% PSL. The control (i.e., traditional) shoe was a New Balance 890v5, weighing 8.6 oz with a 19.0 mm heel profile and 11.0 mm toe profile. The minimalist shoe was a New Balance Minimus Zero v2, weighing 5.9 oz with a 12.8 mm heel profile and 12.0 mm toe profile.

Preferred running speed and PSL were calculated for all conditions over a series of "warm-up" trials while participants wore the control shoe. For these trials, participants were instructed to run overground at a "speed they would select for a 5 km run". Participants ran at an average speed of 3.8 ± 0.5 m/s. Trials were accepted only if the measured speed was within $\pm 5\%$ of the participant's self-selected speed. Running speed was recorded using a pair of timing lights (Banner Multi-Beam; Minneapolis, MN, USA) positioned 1.9 m apart, halfway down a 23 m runway. The PSL during warm-up trials was calculated as follows:

$$PSL = \frac{t_{n \text{ strides}} * v}{n_{\text{strides}}} \quad (1)$$

where, $t_{n \text{ strides}}$ is the time taken to run a given number of strides (n_{strides}), and v is the running speed calculated from the timing lights.

Five markers were placed on the thigh and shank of the right leg to measure each segment's spatial orientation. An additional nine markers were placed on the pelvis, hip, medial and lateral knee, and medial and lateral ankle to identify joint centre locations of the right lower-extremity. Five markers were

also placed on the right shoe in the following locations: heel, first metatarsal head, fifth metatarsal head, dorsal surface of the forefoot, and toe box. A rearfoot coordinate system (proximal to the MTP joint) was created using the heel, first and fifth metatarsal head, dorsal forefoot, and medial/lateral ankle markers. A toe coordinate system (distal to the MTP joint) was created using the first and fifth metatarsal head and toe box markers.

A static motion capture trial was collected as the participants stood upright in each shoe to establish a neutral anatomical coordinate system for each segment. The order of the four running conditions was randomized counterbalanced to reduce bias. Motion capture data were recorded at 240 Hz using eight high-speed video cameras (Motion Analysis Corporation; Santa Rosa, CA, USA). Plantar pressure data were recorded on the right foot at 200 Hz using a Pedar-X pressure-sensing insole (Novel; Minneapolis, MN, USA). A non-functioning Pedar-X insole was placed in the left shoe to avoid any contralateral foot height discrepancy. Ground reaction force data were collected at 2400 Hz using a floor-embedded force platform (Kistler Instruments AG; Winterthur, ZH, Switzerland) located in the centre of the 23 m runway. Markers were adhered to the laboratory floor to constrain participants' stride lengths to either PSL or 90% PSL, depending on condition. Participants were instructed to have their feet land on these markers without visual targeting; if participants did not run at the specified stride length or if visual targeting was suspected, the trial was redone. In general, approximately 3-5 familiarization trials were required to ensure no visual targeting was occurring.

Custom written Matlab code (The MathWorks, Inc.; Natick, MA, USA) was used to analyze the raw motion capture, force platform, and plantar pressure data. Force platform data were downsampled from 2400 Hz to 240 Hz, and both motion capture and force platform data were filtered with a zero-lag low-pass fourth order Butterworth filter with a cutoff frequency of 20 Hz.¹³ Cardan-Euler angles were used to describe segment and joint motion, which were calculated using a flexion-extension, abduction-adduction, internal-external rotation sequence. Segment masses, centre of mass locations, and moments of inertia

were calculated for the thigh, shank, and whole foot using anthropometric data obtained prior to testing.¹⁷ Rearfoot and toe segment masses, centre of mass locations, and moments of inertia were estimated using elliptical cylinder assumptions. A sensitivity analysis illustrated that a tenfold increase in foot segment anthropometrics produced only a 3.4% change in the peak flexion-extension MTP moment.

Plantar pressure data was used to calculate foot strike index (FSI),¹⁸ obtained by dividing the anterior-posterior position of the center of pressure (COP) at 5% of maximum force by foot length. This measure gave an indication of the initial centre of pressure location relative to the plantar surface of the foot, with a value of 0% corresponding to the heel and 100% corresponding to the toe.

Intersegmental joint moments for the MTP, ankle, and knee joints were calculated using an inverse dynamics approach. The MTP joint axis was defined by a line connecting the first and fifth metatarsal head markers, and the MTP joint moment calculation was considered valid only after the COP was distal to the joint axis.¹⁹ Joint angular impulse was calculated as the time integral of the joint moment curve. A cumulative impulse (I_c , N·s) was also calculated by multiplying the angular impulse (I) for one stance phase by the number of strides (n) necessary to reach 5 km:

$$I_c = n \times I \quad (2)$$

where n is the quotient of running distance divided by stride length.¹⁵ Concentric (i.e., positive) and eccentric (i.e., negative) work were calculated from the time integral of the joint power curve, or the product of the joint moment and angular velocity. All data were normalized to 101 time points of stance using a cubic spline interpolation.

MTP, ankle, and knee joint outcome variables were reported for the sagittal plane. Variables were trial-averaged and included the following: FSI, peak joint moments, angular impulse, cumulative impulse, and concentric/eccentric work. Multiple 2×2 factor repeated measures ANOVAs were used to test the outcome variables for effects of shoe type and stride length.²⁰ SPSS (SPSS Inc., Chicago, IL, USA) was

used for all statistical analyses with a criterion alpha level of 0.05. Cohen's d effect sizes were used to compare the relative influence of shoe type and stride length on reducing knee joint loads.

Results

No significant interactions between shoe and stride length were observed for any of the outcome variables examined ($0.479 \leq p \leq 0.979$); the statistical results reported below are for the main effects of shoe and stride length only. FSI was significantly greater during minimalist running conditions ($13.5 \pm 1.9\%$ for control shoe vs. $23.1 \pm 12.3\%$ for minimalist shoe, $p = 0.008$), indicating that the COP at contact was located further anterior during control shoe conditions. Subject- and trial-averaged results from repeated measures ANOVAs are shown in Table 1.

Effect of Shoe Type

Eccentric work at the MTP joint was 23.1% greater when running in the minimalist shoe ($p = 0.002$). Conversely, MTP joint concentric work was reduced in the minimalist shoe by 16.9% ($p = 0.007$). MTP joint peak moment, angular impulse, and cumulative impulse were not significantly different. The ankle joint illustrated a significantly greater peak plantarflexion moment, angular impulse, cumulative impulse, and eccentric work for minimalist shoe conditions (3.8%, 7.1%, 7.3%, 20.7%, respectively; $p \leq 0.001$). Concentric work at the ankle was not affected by shoe type. In contrast to the ankle joint, knee peak moment, angular impulse, and cumulative impulse were significantly lower in the minimalist shoe (-6.1%, -8.4%, -7.9%, respectively; $p \leq 0.021$). Knee concentric and eccentric work were unaffected by shoe type.

Effect of Stride Length Reduction

MTP joint cumulative impulse increased by 12.4% at 90% PSL ($p = 0.025$), while all other MTP output variables were not significantly different. Conversely, ankle angular impulse and concentric work were reduced (-4.1%, -11.7%, respectively; $p \leq 0.037$). Ankle cumulative impulse was 6.5% greater ($p =$

0.007) at the reduced stride length. Ankle joint peak moment and eccentric work were not changed by reducing stride length. Running at 90% PSL also illustrated a significantly lower knee peak moment, angular impulse, cumulative impulse, and concentric and eccentric work (-12.0%, -19.7%, -11.8%, -16.9%, -20.5%, respectively; $p \leq 0.037$).

Discussion

The purpose of this study was to investigate the effects of minimalist shoes and stride length reduction on select kinetic variables of the MTP, ankle, and knee joint during running. In general, we observed that running in minimalist footwear was associated with increased single-stance measures of loading at the MTP and ankle joint, but decreased single-stance measures of loading at the knee joint. Conversely, running with reduced stride length was associated with decreased single-stance measures of loading at the ankle and knee joint. Cumulative loads were greater in the MTP and ankle joints, but lower in the knee joint at reduced stride length.

A limited number of studies have examined MTP joint kinetics during running, and the magnitudes of the peak plantar flexor moments observed herein were similar to that previously reported.¹⁹ The vast majority of work performed at the MTP joint was negative (i.e., eccentric), in which increased energy absorption was displayed during minimalist shoe running. Running in minimalist shoes was associated with an increased ankle peak joint moment, angular impulse, and work (both eccentric and concentric). As the plantar flexor muscles of the MTP joint also cross the ankle, these increased loads and work would place larger energy absorption requirements on the MTP joint. The increased ankle joint loading observed in minimalist shoes may be explained by slight alterations in foot strike pattern. Other studies have illustrated that runners using a forefoot strike pattern demonstrate higher ankle moments,^{5,21} and participants in this study adopted a more anterior foot strike pattern during minimalist shoe conditions. The increased loads and work at the MTP and ankle joint during minimalist shoe conditions may help to

explain some of the incidence of overuse injuries observed in minimalist shoe users, including Achilles tendinopathy, plantar fasciitis, and metatarsal stress fractures.^{7,8}

Epidemiological studies have reported that between 25% to 42% of all running-related injuries occur at the knee,^{22,23} and our results suggest that running in minimalist shoes and at 90% PSL both represent effective strategies to decrease mechanical loads at this joint. Previous studies have illustrated that running with a forefoot strike pattern is associated with lower knee moments in the sagittal and coronal plane.^{5,24} It is interesting to note which strategy, minimalist footwear or stride length reduction, was more effective at decreasing knee joint loading parameters during running, which illustrated reductions during both conditions. Compared to the control shoe at PSL, the Cohen's *d* effect sizes for peak joint moments were -1.48, -0.77, and -1.98 for the control shoe at 90% PSL, minimalist shoe at PSL, and minimalist shoe at 90% PSL, respectively. Thus, reducing stride length was more effective at decreasing knee joint loads than the minimalist shoe, but importantly, incorporation of both load reduction mechanisms appears to have an additive effect.

The ankle and knee joints displayed a significantly lower impulse at 90% PSL. Despite these significant reductions, the cumulative impulse for a 5 km run was only lower at the knee joint; in fact, the cumulative impulse at 90% PSL was significantly greater at the ankle joint. In this regard, it is tempting to conclude that the reduction in angular impulse at 90% PSL is not enough to negate the unfavorable increase in loading cycles for a particular running distance. But extrapolation of this specific cumulative impulse measure to overuse injury potential should be made with caution, as it places an equal emphasis on angular impulse and loading cycles. For example, 2000 strides with an angular impulse of 1000 Nm·s/stride would have the same injury potential as 2500 strides with an angular impulse of 800 Nm·s/stride. Such a linear relationship does not exist for biological tissue, which is readily observed by examining any stress-life plot generated from *ex vivo* fatigue testing of cadaveric materials.²⁵ The relationships between stress magnitude and the number of cycles to failure is well described by inverse

exponential relationships for cartilage²⁶ and tendon,²⁷ and an inverse power relationship for bone.²⁵ Thus, we propose that a more appropriate cumulative impulse measure to account for load-induced tissue damage would place an exponential or power-law weighting on angular impulse, or in the latter case:

$$I_C = nI^m$$

where m is a tissue dependent weighting factor based on the slope of a stressed-life plot, for example $m = 6.6$ in the case of bone.²⁵ The equation above is identical in form to the daily loading stimulus equation proposed by Carter's group²⁸ to predict load-induced tissue adaptation, and there is sufficient evidence to suggest that load-induced tissue damage may serve as a stimulus for biological remodeling.²⁹

Several aspects of this study limit the generalizability of our findings. First, it is important to note that the lower-extremity kinetics observed herein may not necessarily reflect the mechanics of an experienced minimalist shoe runner. Goss and Gross¹ reported that 94% of experienced minimalist shoe runners landed with either a midfoot or forefoot strike pattern. Therefore, our results may be more representative of a traditional shoe runner transitioning to a minimalist shoe. Second, a 10% reduction in stride length may lead to an increase in rating of perceived exertion,⁶ which may change running mechanics due to fatigue. On the other hand, a 10% reduction in stride length does not appear to have a meaningful increase in oxygen consumption or heart rate.³⁰

Conclusions

Running in the minimalist shoe increased joint loads at the MTP and ankle joint, which may help to explain some of the incidence of overuse injuries observed in minimalist shoe users. A 10% reduction in stride length decreased loads at the ankle and knee, but cumulative loads were only lower at the latter joint. Reducing stride length was more effective at decreasing knee joint loads than the minimalist shoe, but both load reduction mechanisms appear to have an additive effect.

Practical Implications

- 263 • Minimalist shoes decreased knee joint loads but increased ankle and MTP joint loads.
- 264 • A 10% reduction in stride length reduced knee and ankle joint loads.
- 265 • Reducing stride length was more effective at decreasing knee joint loads than the minimalist
- 266 shoe, but in combination appear to have an additive effect.

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333 Figures

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335 **Figure 1:** Trial-averaged MTP, ankle, and knee joint moments and powers for a representative subject

336 running in the control and minimalist shoe at PSL. Negative MTP/ankle moments represent

337 plantarflexion. Negative knee moments represent flexion. Positive and negative values of power represent

338 generation and absorption, respectively. Shaded areas are ± 1 SD.

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Figure 2: Trial-averaged MTP, ankle, and knee joint moments and powers for a representative subject running at PSL and 90% PSL in the control shoe. Negative MTP/ankle moments represent plantarflexion. Negative knee moments represent flexion. Positive and negative values of power represent power generation and absorption, respectively. Shaded areas are ± 1 SD.

Table 1: Subject- and trial-averaged kinetic measures for the MTP, ankle, and knee joint while running at preferred speed (± 1 SD).

			Peak Moment (N·m/kg)	Angular Impulse (Nm·s/kg)	Cumulative Impulse for 5 km Distance (Nm·s/kg)	Concentric Work (J/kg)	Eccentric Work (J/kg)
	Shoe Type	Stride Length					
MTP Joint	Control	PSL	0.70 (0.15)	0.0542 (0.01)	98.0 (20.4)	0.0140 (0.005)	0.2009 (0.07)
		90% PSL	0.70 (0.14)	0.0545 (0.01)	108.6 (22.2)	0.0137 (0.006)	0.2013 (0.06)
	Minimalist	PSL	0.73 (0.18)	0.0604 (0.02)	109.1 (29.6)	0.0117 (0.005)	0.2471 (0.08)
		90% PSL	0.73 (0.17)	0.0619 (0.02)	124.2 (36.7)	0.0114 (0.005)	0.2481 (0.07)
Main effect of shoe type (<i>p</i> -value)			0.478	0.157	0.146	0.007 ^a	0.002 ^a
Main effect of stride length (<i>p</i> -value)			0.913	0.802	0.025 ^a	0.704	0.943
Ankle	Control	PSL	3.21 (0.45)	0.39 (0.06)	706.9 (102.3)	0.96 (0.70)	0.546 (0.14)
		90% PSL	3.14 (0.46)	0.37 (0.06)	752.5 (119.0)	0.85 (0.50)	0.532 (0.15)
	Minimalist	PSL	3.34 (0.43)	0.42 (0.06)	758.2 (102.1)	0.87 (0.23)	0.650 (0.16)
		90% PSL	3.25 (0.45)	0.40 (0.06)	807.8 (134.6)	0.77 (0.18)	0.652 (0.23)
Main effect of shoe type (<i>p</i> -value)			0.001 ^a	0.000 ^a	0.000 ^a	0.549	0.001 ^a
Main effect of stride length (<i>p</i> -value)			0.095	0.037 ^a	0.007 ^a	0.020 ^a	0.862
Knee	Control	PSL	2.21 (0.38)	0.19 (0.06)	338.1 (74.0)	0.14 (0.05)	0.63 (0.20)
		90% PSL	1.94 (0.39)	0.15 (0.06)	296.8 (92.1)	0.11 (0.05)	0.50 (0.16)
	Minimalist	PSL	2.07 (0.32)	0.17 (0.04)	310.2 (61.5)	0.13 (0.04)	0.59 (0.20)
		90% PSL	1.82 (0.31)	0.14 (0.05)	275.0 (84.5)	0.11 (0.04)	0.47 (0.18)
Main effect of shoe type (<i>p</i> -value)			0.003 ^a	0.013 ^a	0.021 ^a	0.087	0.004 ^a
Main effect of stride length (<i>p</i> -value)			0.000 ^a	0.001 ^a	0.037 ^a	0.000 ^a	0.000 ^a

Positive peak moments and impulse represent plantarflexion in the MTP and ankle, and extension in the knee. Repeated measures ANOVA results shown below each measure. ^aSignificant effect ($p < 0.05$).