



Original research

Does increased midsole bending stiffness of sport shoes redistribute lower limb joint work during running?



Sasa Cigoja^{a,*}, Colin R. Firminger^b, Michael J. Asmussen^d, Jared R. Fletcher^c,
W. Brent Edwards^{a,b}, Benno M. Nigg^a

^a Human Performance Laboratory, Faculty of Kinesiology, University of Calgary, Canada

^b Biomedical Engineering Graduate Program, University of Calgary, Canada

^c Department of Health and Physical Education, Mount Royal University, Canada

^d Department of Biology, Faculty of Science & Technology, Mount Royal University, Canada

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ABSTRACT

Objectives: To investigate if lower limb joint work is redistributed when running in a shoe with increased midsole bending stiffness compared to a control shoe.

Design: Within-subject with two conditions: (1) commercially available running shoe and (2) the same shoe with carbon fibre inserts to increase midsole bending stiffness.

Methods: Thirteen male, recreational runners ran on an instrumented treadmill at 3.5 m/s in each of the two shoe conditions while motion capture and force platform data were collected. Positive and negative metatarsophalangeal (MTP), ankle, knee, and hip joint work were calculated and statistically compared between conditions.

Results: Running in the stiff condition (with carbon fibre inserts) resulted in significantly more positive work and less negative work at the MTP joint, and less positive work at the knee joint.

Conclusions: Increased midsole bending stiffness resulted in a redistribution of positive lower limb joint work from the knee to the MTP joint. A larger MTP joint plantarflexor moment due to increased vGRF at the instant of peak positive power and an earlier onset of MTP joint plantarflexion velocity were identified as the reasons for lower limb joint work redistribution.

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Practical implications

- Increased midsole bending stiffness resulted in more positive work performed at the MTP joint and less positive work performed at the knee joint.
- Higher joint moments at the MTP joint and an earlier onset of MTP plantarflexion joint velocity in the stiff condition were related to redistribution of lower limb joint work.
- It is speculated that higher vGRF in the stiff condition could indicate potential energy return properties of the carbon fibre plate.

1. Introduction

Midsole bending stiffness (MBS) of sport shoes has been shown to affect a variety of biomechanical,^{1–3} performance,^{4–6} and physiological^{7–9} variables during different athletic activities. Ste-

fanyshyn & Nigg¹⁰ were the first to investigate the mechanical work contribution of the lower limb joints during running and sprinting. Their findings showed that the metatarsophalangeal (MTP) joint largely performed negative work, or mechanical energy absorption, during the stance phase of running and sprinting. The authors speculated that this phenomenon occurred because the MTP joint performed mainly dorsiflexion during the stance phase of running. Therefore, Stefanyshyn & Nigg¹⁰ hypothesized that limiting the amount of MTP joint dorsiflexion would potentially reduce the amount of energy loss at the joint. One potential method to reduce the amount of MTP joint dorsiflexion is by increasing shoe MBS. It was hypothesized by these authors that this reduced energy loss could be used to increase athletic performance.⁶ Stefanyshyn & Nigg⁶ observed that participants jumped higher in a stiff shoe compared to a control shoe when performing maximal effort vertical jumps. The amount of energy loss at the MTP joint was also reduced with increased shoe MBS. Because it was shown that the negative work done at the MTP joint was approximately twice as high in sprinting than in jumping,^{10,11} it was speculated that similar performance benefits would be observed during a sprint-

* Corresponding author.

E-mail address: sasa.cigoja1@ucalgary.ca (S. Cigoja).

ing task. Stefanyshyn & Fusco⁵ examined if systematic increases in MBS resulted in sprinting performance improvements. Their results showed that sprinting performance increased in 85% of their participants with higher MBS, but if the stiffness of the shoes was increased beyond a specific threshold, for some participants, the performance declined.

The underlying functional mechanisms of why MBS affects lower limb biomechanics and athletic performance are not well understood. Two primary mechanisms were introduced by Nigg & Segesser¹² and Nigg, et al.¹³ to explain how footwear may improve athletic performance: (1) the principle of energy storage and return, and (2) the principle of minimizing energy loss. In brief, the principle of energy storage and return states that the maximum possible energy storage and return can be estimated by considering the midsole as an idealized (rotational) spring. The principle of minimizing energy loss suggests that if the negative work performed by a joint is minimized, athletic performance can be increased because muscles perform less eccentric work, and therefore less energy is dissipated. Stefanyshyn & Nigg⁶ attempted to relate the decreased energy loss at the MTP joint in a stiff shoe condition with increases in potential energy during a jumping task. Although no statistics were provided due to the low number of participants that were compared, no linear relationship between reduction in MTP energy loss and increased potential energy was identified.

Sanno et al.¹⁴ reported that positive joint work was redistributed towards proximal lower limb joints during a prolonged fatiguing run. The authors speculated that this may increase metabolic cost of running because the joint work was performed by proximal muscle-tendon units, which have been assumed to be less equipped for storage and return of energy^{15,16} and require more energy to generate the same amount of force.¹⁶ Based on the conclusions by Sanno et al.,¹⁴ it could be speculated that redistributing lower limb joint work towards distal joints during running would be energetically more beneficial. The total lower limb joint work during constant velocity running, however, should remain the same. If the MTP joint performed less negative work with increased MBS,⁶ then other joints should compensate for this change in joint work. Whether the MBS of sport shoes is able to cause a redistribution of lower limb joint work, however, is unknown. Therefore, the purpose of this study was to investigate if lower limb joint work is redistributed when running in a shoe with increased MBS. It was hypothesized that the negative MTP joint work would decrease because increased MBS would limit the amount of MTP joint dorsiflexion. It was further hypothesized that due to the bending of the carbon fibre plate, elastic energy would be stored and returned to the shoe-foot interface, which would be observed in higher positive MTP joint work. If total lower limb joint work remains the same, more proximal joints would need to compensate (i.e., decrease work) for the increased MTP joint work.

2. Methods

Thirteen male, recreational runners (mean \pm SD; height: 162.8 \pm 0.5 cm, body mass: 70.5 \pm 8.3 kg) participated in this study. All participants were moderately active, free of neuromuscular disorders, and had no lower limb injuries in the past six months. The study was approved by the University of Calgary Conjoint Health Research Ethics Board: REB17-1520, and all participants gave written informed consent prior to participating in the study. Subjects ran on an instrumented treadmill (Bertec Corporation, Columbus, USA) at 3.5 m/s in two shoe conditions. The control condition consisted of a commercially available running shoe (Nike Free 5.0, Nike Inc., Beaverton, USA). The stiff condition was achieved by inserting custom carbon fibre plates into the control shoe. The carbon fibre plates were inserted along the full length of the shoe and placed



Fig. 1. Shoe marker set: (1) distal head of 1st metatarsal head, (2) medial forefoot, (3) mid forefoot, (4) lateral forefoot, (5) distal head of fifth metatarsal, (6) lateral heel, (7) proximal heel, (8) medial heel. Markers 1 and 8 were mounted directly on the participant's skin through holes that were cut out of the shoe.

on top of the midsole to maintain close proximity of the plate to the foot. The shoe's sockliner was placed on top of the carbon fibre plate, however, because direct contact of the foot with the plate was perceived as uncomfortable during pilot testing.

The MBS of the entire shoe was determined using a three-point bending test in which, the forefoot of the shoe was placed on a custom-made structure with two supporting pins (160 mm apart). A compressive force was applied vertically on the shoe in the area of the MTP joint using an indenter that was attached to an 858 Mini Bionix II testing machine (MTS Systems Corporation, Eden Prairie, USA). The machine was set to displace the shoe by 15 mm at a speed of 10 mm/s. This was repeated ten times for each stiffness condition. The loading curves for all ten cycles per stiffness condition were identified. The stiffness of the entire shoe was determined for 80–90% of each loading curve (linear portion of the force-displacement curve) and averaged across all ten cycles. The bending stiffness for the control and stiff conditions were 1.2 N/mm and 11.9 N/mm, respectively, showing that there was a 10-fold increase in MBS. The mass of the shoe conditions was determined using a laboratory balance (Model PG4002-S, Mettler-Toledo, Columbus, USA) and was 225.67 and 289.10 g for the control and stiff condition, respectively.

For in vivo biomechanical testing, the right lower limb and the pelvis of each subject was equipped with 24 retroreflective markers. The markers were mounted on the following anatomical landmarks: distal phalanx of the great toe, third toe, and fifth toe; distal heads of the first and fifth metatarsals; medial, lateral, and proximal heel; medial and lateral malleolus; proximal, distal, and posterior shank; medial and lateral epicondyles; proximal, distal, and posterior thigh; left and right greater trochanter; right and left anterior superior iliac spine and right and left posterior superior iliac spine. Holes were cut in the shoe to allow for the application of markers on the skin overlying the distal head of the first metatarsal and the medial heel. All other foot markers were placed on the outside of the shoe (Fig. 1). Kinematic data were collected using eight high speed video cameras (Motion Analysis Corporation, Santa Rosa, USA) operating at a sampling frequency of 240 Hz. Ground reaction forces were captured at 1000 Hz using a single force plate instrumented in the treadmill. The order of conditions in which participants performed running trials was randomized. Participants performed familiarization trials to get accustomed to the running speed and footwear conditions. After familiarization,

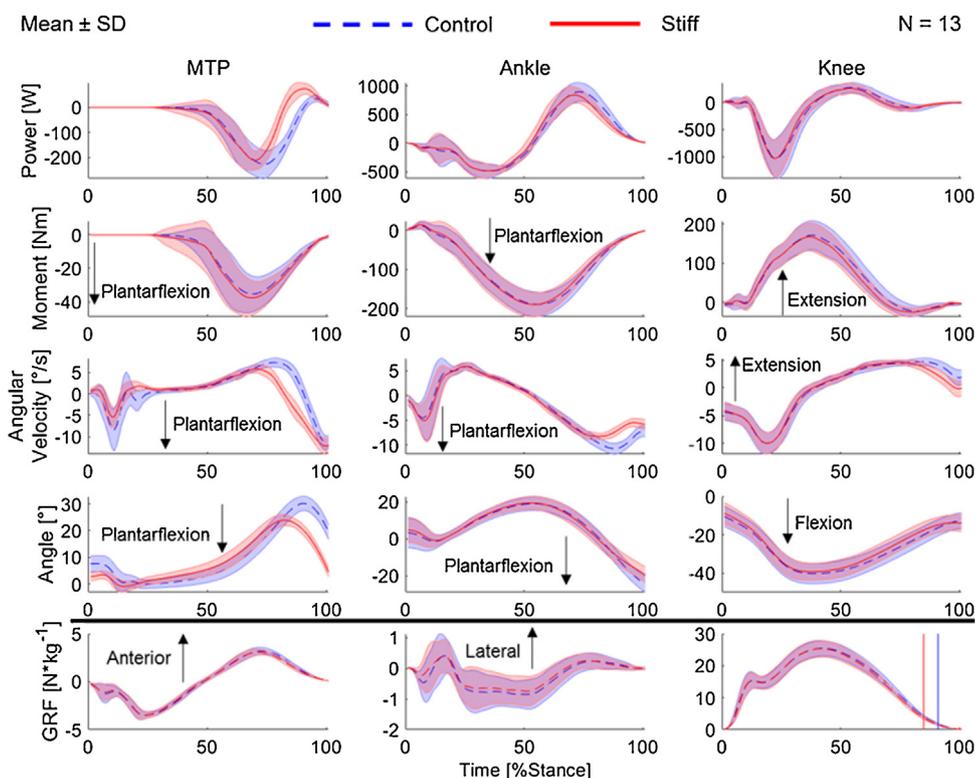


Fig. 2. Group mean \pm standard deviation (shaded area) of the metatarsophalangeal (MTP; left column), ankle (centre column), and knee (right column) joint power (top row), moment (2nd row), angular velocity (3rd row), and angle (4th row) in the control (blue broken line) and stiff (red full line) conditions. The 5th row illustrates antero-posterior (left), medio-lateral (middle), and vertical (right) ground reaction forces (GRF). The vertical lines indicate when positive MTP joint power was initiated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(179.87 ± 29.79) condition. Running in the stiff shoe condition, however, resulted in significantly higher positive MTP joint work ($p \leq 0.001$, $d = 3.13$) and lower positive knee joint work ($p \leq 0.05$; $d = 0.34$) compared to the control condition. The average positive joint work for the MTP, ankle, knee, and hip joints were $2.66 \pm 0.91\%$, $61.77 \pm 6.33\%$, $16.52 \pm 4.48\%$, and $19.05 \pm 7.61\%$ of the total lower limb positive work in the stiff condition compared to $0.67 \pm 0.27\%$, $63.47 \pm 7.39\%$, $17.85 \pm 4.93\%$, and $18.02 \pm 6.98\%$ in the control condition, respectively. There was significantly ($p \leq 0.05$, $d = 0.77$) less negative work in the MTP joint when running in the stiff compared to the control condition. No other differences in negative joint work between the control and stiff condition were observed. The average negative joint work for the MTP, ankle, knee, and hip joints were $11.36 \pm 3.19\%$, $35.19 \pm 5.82\%$, $46.23 \pm 9.35\%$, and $7.23 \pm 4.01\%$ of the total lower limb negative work in the stiff condition compared to $14.20 \pm 4.47\%$, $34.50 \pm 6.56\%$, $44.49 \pm 10.10\%$, and $6.80 \pm 4.43\%$ in the control condition, respectively. Body mass normalized joint work is presented in Table 1.

At the instant of peak positive MTP joint power, MTP joint plantarflexion moment was significantly ($p \leq 0.001$, $d = 2.68$) higher in the stiff (-14.30 ± 3.38 Nm) compared to the control (-7.14 ± 1.67 Nm) condition (Fig. 2). There was no difference ($p = 0.27$, $d = 0.40$) in MTP joint angular velocity at the instant of peak positive MTP joint power between the control ($-8.53 \pm 1.43^\circ/\text{s}$) and stiff ($-7.99 \pm 1.28^\circ/\text{s}$) condition. MTP joint plantarflexion, however, was initiated significantly earlier ($p \leq 0.001$, $d = 5.15$) during stance in the stiff ($85.55 \pm 1.12\%$ Stance) compared to the control ($91.41 \pm 1.16\%$ Stance) condition. Furthermore, the average vGRF was significantly ($p \leq 0.01$, $d = 1.03$) higher in the stiff (2.43 ± 0.82 N kg $^{-1}$) compared to the control condition (1.43 ± 1.09 N kg $^{-1}$) at the instants of positive MTP joint power. There was no difference ($p = 0.60$, $d = 0.14$), however, in the vGRF

moment arm to the MTP joint centre between the footwear conditions during this time.

4. Discussion

The purpose of this study was to investigate if a redistribution of lower limb joint work occurs when running in a shoe with increased MBS. It was hypothesized that the negative MTP joint work would decrease because the increased MBS would limit the amount of MTP joint dorsiflexion. It was further hypothesized that due to the bending of the carbon fibre plate, elastic energy would be stored and returned to the shoe-foot interface, which would be observed in higher positive MTP joint work. If total lower limb joint work remains the same, more proximal joints would need to compensate for the increased MTP joint work. The findings of this study suggest that increased MBS resulted in a redistribution of lower limb joint work, where significantly more positive work was performed at the MTP joint and less positive work was performed at the knee joint. Further, significantly less negative work was performed at the MTP joint when running in the stiff condition. No significant differences were observed at the ankle and hip joints.

Two major factors were identified as the underlying mechanisms that led to this energetic redistribution with increased MBS. First, the peak MTP joint plantarflexion moment, at the instance of peak positive joint power, was significantly higher in the stiff condition compared to the control condition. Second, the instance when MTP joint plantarflexion was initiated during the stance phase was significantly earlier in the stiff shoe compared to the control condition. A combination of an earlier onset of MTP joint plantarflexion and larger MTP joint moments resulted in higher positive power, and therefore greater positive work at the joint.

Higher MTP joint moments in the stiff condition may be the result of increased muscle forces, which would potentially result

in higher metabolic cost of performing an athletic task; however, this would contradict various experimental findings that showed performance benefits in footwear conditions with increased MBS during long-term endurance events.^{7,8} Another explanation could be that MTP joint moments were increased due to additional forces generated by the carbon fibre plate. The carbon fibre plate may act as a torsional spring, which stored and returned elastic energy as the MTP joint underwent rotational deformation during the stance phase of running. For energy to be returned effectively by a sport shoe, however, it must be returned at the right location, time, and frequency.¹² Our results cannot directly address the time and frequency aspects of energy return, but can address the location factor. If the carbon fibre plate stored energy as a torsional spring, it would return it at the location of the foot, which is in contact with the ground at toe-off (i.e., the forefoot). In our study, we observed an increase in average vGRF in the stiff condition during the instants of positive MTP joint power. Since the forefoot was in contact with the ground at late stance and during these instants the MTP joint moment and, correspondingly, the MTP joint power was increased, it is suggested that the carbon fibre plate likely returned energy at the correct location. Future efforts should explore how a carbon fibre plate could address the time and frequency aspects of optimal energy return of sports shoes.

Our findings showed that significantly more positive work can be performed at the MTP joint with a stiffer midsole due to increased MTP joint moments and an earlier onset of MTP joint plantarflexion velocity. The first studies that investigated the effects of MBS on lower limb biomechanics and the energetic contributions of the MTP joint in general reported minimal to no plantarflexion angular displacement and velocity during the stance phase of running.^{8,10} More recent studies, however, have shown increased MTP joint plantarflexion angular displacement and velocity when running in a stiff shoe compared to a less stiff condition.^{1,21} More specifically, when the MTP angular displacement and velocity curves of these studies were inspected carefully, it can descriptively be observed that the onset of plantarflexion occurred earlier during stance phase when running in stiff conditions. An earlier onset of plantarflexion means that positive joint power is initiated earlier as well. This suggests that either the muscles crossing the joint performed less eccentric work and/or the carbon fibre plates returned energy to the runner. Both would be positive effects for the athlete.

One explanation as to why the findings regarding the MTP joint energetics and kinematics were different in this study compared to previously reported results^{1,6,10} could be that, in this study, the retroreflective marker that was placed on the distal head of the first metatarsal was applied directly on the skin overlaying the anatomical landmark. For this, holes with a diameter of approximately 20 mm were cut out of the shoe and participants were running without socks. Also, Stefanyshyn & Nigg¹⁰ performed only a sagittal plane analysis where markers were applied on the heel of a shoe, the shoe upper overlaying the fifth metatarsal head, and the toe box. The studies performed by Roy & Stefanyshyn⁸ and Hoogkamer et al.¹ included a 3-dimensional kinematic analysis where the MTP joint was estimated using markers placed on the upper material of the shoes overlaying the first and fifth metatarsal heads. However, in the study by Oh & Park²¹ the authors applied markers directly on the skin overlaying the distal heads of the first and fifth metatarsal heads. Similarly to our results, Oh & Park²¹ also showed an earlier onset of MTP joint plantarflexion in the stiff condition, suggesting that marker placement was the major contributor to differences across studies. Further, the study published by Hoogkamer et al.¹ found significant joint work differences at the ankle but no differences at the knee joint. Another reason as to why the findings in this study differed from previous work could be that, here, the MBS in the stiff condition was ten times higher compared to the

control condition. In Hoogkamer et al.¹ work, however, the stiffest condition was “only” twice as stiff as the most compliant condition.

There were some limitations associated with this work. The ground reaction forces were not partitioned for individual foot segments. Instead, the moment around the MTP joint generated by the GRF was set to zero until the COP progressed distally to the MTP joint axis.^{1,10,18} This approach has been shown to overestimate the peak MTP joint plantarflexion moment by up to 17% while underestimating total angular impulse by up to 31%.²² This method, however, has only been shown to affect the negative but not the positive MTP joint power. Further, due to the fact that this study was of a within-subject design, it is speculated that the errors associated with this method would affect MTP joint moments and powers in both shoe conditions similarly. This means that absolute values may be affected by this method, but the conclusions drawn from the results would still be accurate. Once validated, a weighted probability approach to partition the GRF as suggested by Riddick et al.²³ could help to overcome this methodological limitation.

Further, the mass of the shoe varied between stiffness conditions, which could have influenced the results. If increased shoe mass in the stiff condition affected lower limb biomechanics, then increased total joint work was expected to be observed. This, however, was not the case as there was no significant difference in total lower limb joint work between stiffness conditions. Therefore, it is speculated that the difference in shoe mass of 64 g had only minimal effects on lower limb biomechanics.

5. Conclusion

In conclusion, increased MBS resulted in a redistribution of positive lower limb joint work from the knee to the MTP joint. Significantly larger MTP joint plantarflexor moments due to increased vGRF at the instant of peak positive power and an earlier onset of MTP plantarflexion joint velocity were identified as the underlying mechanism of lower limb joint work redistribution. This could be indicative of potential energy return properties of the carbon fibre plate.

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