CAN INCREASED MIDSOLE BENDING STIFFNESS OF SPORT SHOES DELAY THE ONSET OF LOWER LIMB JOINT WORK REDISTRIBUTION DURING A PROLONGED RUN?

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Prolonged running has been shown to result in a redistribution of positive lower limb joint work from distal to proximal joints. Running footwear with increased midsole bending stiffness (MBS) has been shown to redistribute lower limb joint work from proximal to distal joints. How increased MBS of running shoes can affect joint work redistribution during a prolonged run, however, is unknown. Therefore, the purpose of this study was to investigate if increasing the MBS of running shoes can delay the onset of positive lower limb joint work redistribution during a prolonged run. Thirteen trained male runners (current 10 km time < 44 min.) performed 10-km runs at 90% of their speed at lactate threshold (sLT) in a control and stiff shoe condition, respectively. Prolonged running resulted in a redistribution of positive lower limb joint work from distal to proximal joints in both shoe conditions. The onset of joint work redistribution, however, was delayed at the metatarsophalangeal and ankle joint when running in the stiff shoe condition. A delayed onset of lower limb joint work redistribution in the stiff condition may result in greater energy stored and returned in distal passive-elastic structures (i.e., Achilles tendon), reducing lower limb muscle work later into the prolonged run. Also, less active muscle volume would be required to perform the same total amount of positive mechanical work when running in the stiff condition because the ankle plantarflexor muscles have less volume than the knee extensor muscles. These results contribute to the notion that footwear with increased MBS likely result in lower metabolic cost, due to delays in distal to proximal lower limb joint work redistribution.

KEYWORDS: running, mechanics, midsole, stiffness, shoes.

INTRODUCTION: A recent study reported that prolonged running resulted in a redistribution of lower limb joint work, with more positive work performed at proximal (i.e., knee) compared to distal joints (i.e., ankle) (Sanno et al., 2018). Under the assumption that tendons can store and return relevant amounts of strain energy during running, Sanno et al. (2018) concluded that a redistribution of positive lower limb joint work towards more proximal joints is disadvantageous for long-distance running performance because muscle-tendon units (MTU) surrounding the ankle joint (e.g., triceps surae and Achilles tendon) are thought to be better equipped for storage and return of elastic energy compared to MTUs surrounding the knee joint (Alexander, 1984). Furthermore, if prolonged running resulted in increased positive work at the knee joint and the MTUs surrounding this joint are not as well equipped for energy storage and return, the additional work must be performed by the muscle in series with the tendon. This additional muscle work would require a greater active muscle volume, elevating the metabolic cost (Fletcher & MacIntosh, 2017). This could be disadvantageous for long-distance running performance because metabolic cost is one of the key determinants of distance running performance (Di Prampero et al., 1993).

It can be speculated that if the onset of lower limb joint work redistribution was delayed, performance benefits during long-distance running events could be achieved. One footwear feature that can redistribute lower limb joint work from proximal to distal joints is the increased midsole bending stiffness (MBS) (Cigoja et al., 2019). The MBS of sport shoes has been shown to have a great effect on biomechanical (Hoogkamer et al., 2019), physiological (Hoogkamer et al., 2018), and performance (Stefanyshyn & Nigg, 2000) variables during long-distance running events. Cigoja et al. (2019) demonstrated that running in footwear with increased MBS resulted in more positive work performed at the metatarsophalangeal (MTP) and less positive work performed at the knee joint. This was interpreted as a redistribution of positive lower limb

joint work from proximal to distal joints. Whether this redistribution of joint work in shoes with increased MBS can also be observed during a prolonged run, however, is unknown.
For this reason, the purpose of this study was to investigate if running in shoes with increased MBS can delay the onset of lower limb joint work redistribution from distal to proximal joints during a prolonged run. It was hypothesized that running with increased MBS would result in a delayed decrease of positive ankle joint work and delayed increase of positive knee joint work during a 10-km run.

METHODS: Thirteen trained male runners (mean ± SD; age: 29.9 ± 6.0 yrs., height: 1.79 ± 0.08 m, mass: 71.8 ± 10.5 kg) visited the laboratory on three separate occasions. Participants were included in this study if they were able to run 10 km in under 44 min., were free from lower limb injuries in the past six months, and fit a size 9, 10, or 11 US running shoe. On the first visit, individual speed at lactate threshold (sLT) was determined based off methods described elsewhere (Fletcher et al., 2009) while participants ran on a treadmill (Bertec, Columbus, USA) with no gradient. In brief, participants first performed a 5-min. warm-up at self-selected speed. Immediately after the warm-up, a fingertip blood sample was taken to determine resting blood lactate concentration (Lactate Pro, Sports Resource Group Inc., Minneapolis, USA). After the warm-up, the treadmill belt speed was increased by 0.8 km/h every two minutes, after which blood lactate concentration was measured. This was repeated until blood lactate concentration rose more than 1 mM from the previous sample. sLT was determined as the speed at the stage preceding the last stage.
On the second and third visits, respectively, participants performed a 10-km run at 90% of the individual sLT while wearing a control or stiff running shoe. The control condition consisted of a Nike Free Run 2018 (Nike Inc., Beaverton, USA) shoe. The stiff condition was achieved by inserting straight carbon fibre plates between the factory insole and the midsole, and along the full length of the shoe. The order of shoe conditions was randomized. The MBS for the control and stiff condition were 1.69 and 13.44 N/mm as determined by a 3-point bending test (Cigoja et al., 2019). Three-dimensional (3D) kinematics and kinetics of the right lower limb were recorded at 200 and 1000 Hz using eight high speed cameras (Vicon, Oxford, USA) and a force-instrumented treadmill (Bertec, Columbus, USA), respectively. A 2-min. familiarization trial was performed to allow participants to get accustomed to the running speed and footwear condition. Baseline kinematic and kinetic data were measured for 30 seconds immediately after the familiarization trial and subsequently recorded every 500 m during the 10-km runs. This resulted in 21 bouts of approximately 35-40 steps of the right leg per subject and per footwear condition, respectively. The stance phases of the middle 30 steps were identified and used for further analyses.
Raw data were analysed using a custom written MATLAB code (Version 2019a; The MathWorks Inc., Natick, USA). To determine 3D metatarsophalangeal, ankle, knee, and hip joint kinematics and kinetics, marker and force data were filtered using a dual pass 2^{nd} order Butterworth filter with a cut-off frequency of 50 Hz. A Newton-Euler approach was used to describe joint motion and an inverse dynamics approach was used to calculate sagittal joint moments. Joint mechanical powers were calculated as the product of joint moment and angular velocity. Positive and negative mechanical work was determined as the integral of the positive and negative joint power-time curves over the stance phase, respectively. Joint-specific positive work was expressed relative to total lower limb positive work performed during the stance phase of running. After confirming normal distributions of the outcome measures using Shapiro-Wilk tests, repeated measures analysis of variance was performed (SPSS Statistics 26; IBM Corporation, Armonk USA) to test for significant ($\alpha = 0.05$) differences in positive joint work comparing all time points to baseline. p-values for individual comparisons were adjusted using the Benjamini & Hochberg method (Benjamini & Hochberg, 1995). Effect size estimates were calculated using Cohen's d, where effect sizes of ≥0.2 were interpreted as small, ≥0.5 as medium, and ≥0.8 as large (Sanno et al., 2018).

RESULTS: Compared to baseline, positive MTP joint work was significantly reduced at 3.5 km in the control condition; whereas, there was no significant effect of distance on positive MTP joint work in the stiff condition (Figure 1). At the ankle joint, the first significant difference in positive work occurred at 5.5 km in the stiff compared to 0.5 km in the control condition. At the knee joint, the first significant difference in positive work occurred at 3.5 km for both shoe conditions. There were no differences in positive hip joint work across conditions or distance.

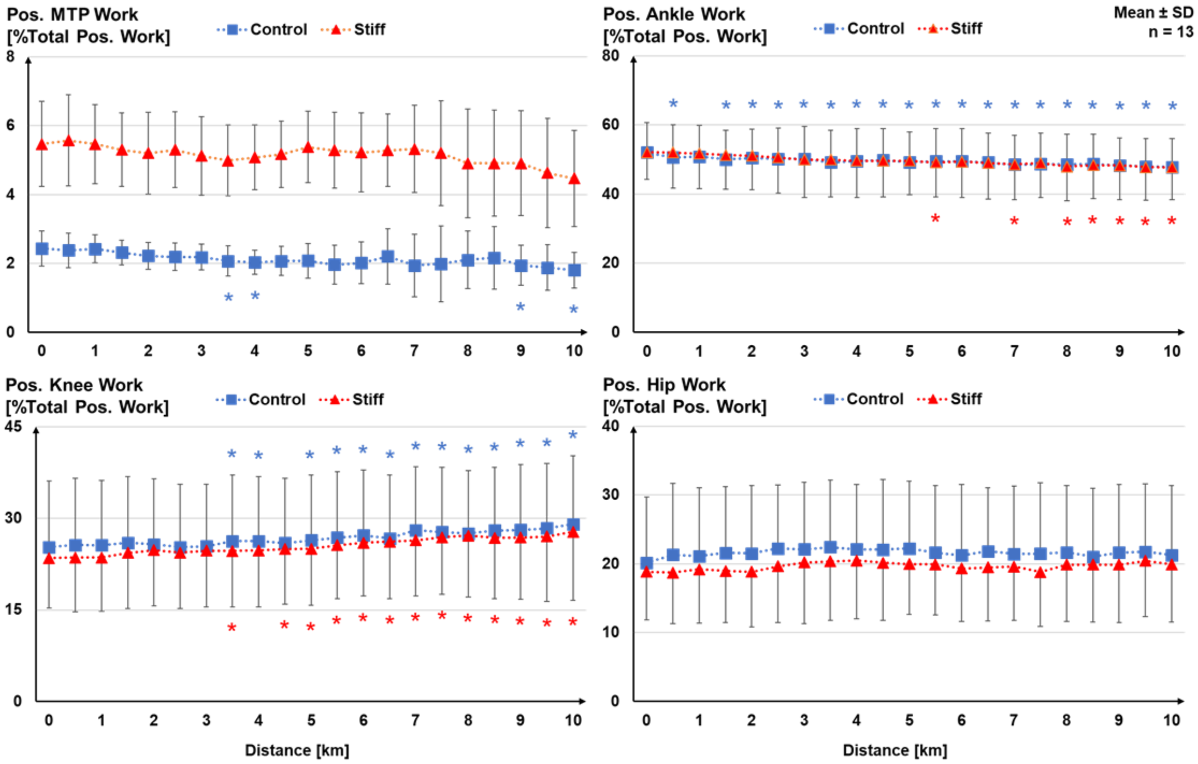

Figure 1: Average (±SD) positive metatarsophalangeal (MTP; top-left), ankle (top-right), knee (bottom-left), and hip (bottom-right) joint work in the control (blue squares) and stiff (red triangles) shoe condition during a 10-km run at 90% of individual speed at lactate threshold. * represent significant ($p < 0.05$) differences relative to the beginning of the run (i.e., 0 km).

When comparing the end of the run to the baseline measurement, running in the control condition resulted in a significant decrease in positive MTP joint work ($p = 0.02$, $d = 1.22$), decrease in positive ankle joint work ($p < 0.001$, $d = 0.50$), increase in positive knee joint work ($p < 0.001$, $d = 0.34$), and no change ($p = 0.37$, $d = 0.11$) in positive hip joint work (Table 1). Prolonged running in the stiff condition resulted in decreased ankle ($p < 0.001$, $d = 0.50$) and increased knee ($p = 0.01$, $d = 0.44$) joint work. There was no change in positive MTP ($p = 0.08$, $d = 0.62$) or hip ($p = 0.51$, $d = 0.14$) joint work between the beginning and end of the run.

Table 1: Average (SD) positive (pos.) metatarsophalangeal (MTP), ankle, knee, and hip joint work at the beginning (0 km) and end (10 km) of the run in the control and stiff shoe condition relative to total positive lower limb joint work. * represent significant ($p < 0.05$) distance effects.

Pos. Work [%Total Pos. Work]		MTP	Ankle	Knee	Hip
Control	0 km	2.44 (0.52)	52.09 (8.66)	25.30 (10.81)	20.18 (9.52)
	10 km	1.81* (0.52)	47.83* (8.31)	29.06* (11.21)	21.30 (10.09)
Stiff	0 km	5.47 (1.23)	52.16 (7.93)	23.52 (8.20)	18.86 (7.03)
	10 km	4.47 (1.39)	47.78* (9.39)	27.80* (11.24)	19.95 (8.40)

DISCUSSION: The purpose of this study was to investigate if the onset of lower limb joint work redistribution from distal to proximal joints during a prolonged run could be delayed by running in footwear with increased MBS. The findings of this study showed that the onset of lower limb joint work redistribution was delayed at more distal joints when running in the stiff shoe condition. This could be interpreted as a metabolically-positive effect because redistribution of positive work towards more proximal joints would require activation of greater muscle volume. Knee extensor muscles (i.e., quadriceps) have longer muscle fascicles and larger cross-sectional areas compared to ankle extensor muscles (i.e., triceps surae). This is speculated to result in more adenosine triphosphate (ATP) consumed by the muscle, and therefore increase the metabolic cost of muscle contraction (Fletcher & MacIntosh, 2017). Furthermore, muscles with shorter fascicles have fewer sarcomeres in series and are thought to consume proportionally less ATP per unit force compared to muscles with longer fascicles under similar activation levels (Roberts et al., 1998). Lastly, under the assumption that tendons are able to store and return relevant amounts of strain energy, a delayed onset of joint work redistribution towards more proximal joints could indicate that the Achilles tendon potentially returns energy to the athlete over an extended period of time (Sanno et al., 2018); thus, reducing the need for additional muscle work (Fletcher & MacIntosh, 2017).

CONCLUSION: Prolonged running in footwear with increased MBS resulted in a delayed onset of lower limb joint work redistribution from distal to proximal joints compared to a control condition. This delayed onset of joint work redistribution towards more proximal joints could be speculated to be metabolically beneficial because MTUs crossing distal joints are thought to be better equipped for elastic energy storage and return and have smaller muscle volume compared to MTUs crossing more proximal joints. Furthermore, this delayed onset of lower limb joint work redistribution could be related to previously reported performance benefits when running in footwear with increased MBS (Hoogkamer et al., 2018).

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