TARGETED CHANGES IN FOOTWEAR UPPER STRETCH IMPROVES RUNNING PERFORMANCE AND FOOTWEAR FIT

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The feet are completely enclosed by shoes when performing athletic activities. However, footwear uppers are often overlooked when studying running performance. We sought to understand how targeted changes in the upper stiffness can influence running centre-of-mass (COM) work and footwear fit, via plantar pressure, with ten participants running at 3 m/s. We also investigated the relationship between peak toe pressure and COM work. We found that having a stretchy material over the cuneiforms with a stiffer material across the metatarsals and talus improved running performance by reducing the amount of COM work to run at a set speed. This configuration also improved qualitative fit and reduced peak toe pressure, a quantitative measure of fit. Finally, we found peak toe pressure is associated with COM work. This metric can be used outside-the-lab to understand fit and performance.

KEYWORDS: Shoe Upper Stiffness, Wearable Sensors, Centre-of-Mass Work

INTRODUCTION: The feet are completely enclosed by shoes when performing most athletic activities. While footwear features such as the midsole receive extensive research, aspects such as footwear uppers are often overlooked (Hoitz et al., 2020). Recent studies demonstrate that augmenting the shoe upper influences agility performance by reducing the amount of ankle joint work and reducing contact time (Subramanium et al., 2021); and replacing laces with a BOA wrap can also improve agility performance by reducing contact time (Pryhoda et al., 2020). The BOA wrap also influences outdoor trail running performance by increasing running speed with no change in exertion (Honert et al., 2023). These performance improvements with the BOA wrap are a result of improved footwear fit (Honert et al., 2023; Pryhoda et al., 2020). Fit can be evaluated qualitatively but also quantitatively through plantar pressure, with improved fit characterized by a higher heel contact area and lower peak toe pressures (Dobson et al., 2018; Hagen & Hennig, 2009).

The BOA wrap encompasses the dorsum of the foot from the talus to the metatarsophalangeal joint (Figure 1) and can improve athletic performance and footwear fit (Honert et al., 2023; Pryhoda et al., 2020). While there appears to be an optimum level of stiffness for the entire wrap to improve agility performance (Luftglass et al., 2023), it is unknown if changing stiffness in targeted locations of the BOA wrap can influence running performance. In prosthetic socket research, where the connection to the residual limb is of upmost importance to gait, impedance matching the residual limb to the socket (e.g., compliant materials interfacing with bony prominences) reduced residual limb pressures and improves prosthetic socket comfort (Sengeh & Herr, 2013). As a result, the primary aim of this study was to understand how changing the stiffness of the BOA wrapping panel over the boney prominence of the cuniforms can influence running performance and footwear fit. As this study was performed in-the-lab, we evaluated running performance with changes in COM work. This metric provides a whole-body work summary, which contains the summed ankle, knee, and hip joint work (Riddick & Kuo, 2016). Previous reductions in mechanical work from footwear interventions have resulted in reduced metabolic cost and improved running performance (Hoogkamer et al., 2018, 2019). Additionally, we sought to understand if plantar pressure metrics from wearable sensors can predict running performance, which could enable footwear testing in more ecological terrain. Many performance metrics, such as mechanical work, require a laboratory setting to collect the necessary biomechanical signals, limiting the applicability of the findings. Wearable sensors, such as plantar pressure, enable footwear testing outside of the lab (Honert et al., 2023) and may provide an avenue for understanding footwear performance in addition to fit.

METHODS: Ten male runners (mean ± standard deviation, height: 1.77 ± 0.05 m, mass: 79.4 ± 9.0 kg, age: 36 ± years) provided consent to run on an instrumented treadmill (1000 Hz, Bertec, Columbus, USA) at 3.0 m/s with three different shoes that only varied in midfoot panel stiffness (Figure 1). The participants varied in ability from recreational runners to ultra marathon runners. The foot strike for each runner was not standardized. The athletes ran in each shoe for one minute in a randomized order with plantar pressure sensors placed in the shoes (100 Hz, XSENSOR, Calgary, CAN). After wearing each shoe, subjects rated the overall fit on a scale of 0 (worst) to 10 (best).
The shoes (La Sportiva Cyklon) only differed in the upper, which was retrofitted with a three-panel wrap (see depiction in Figure 1). The instep and forefoot panels were both the same stiffness (23 N/mm), while the midfoot panel stiffness varied between the three shoes and was 2, 14, and 23 N/mm, respectively. The panel stiffness was characterized with samples of the material (2.5 cm x 15.2 cm) using cyclic tensile testing (500 Hz, ZwickRoell, Ulm, DEU). The samples were cyclically loaded 175 times to 40 N at 1 Hz while recording force and displacement. The average slopes of the force-displacement curves between 20 and 60% of extension from the final 75 cycles were averaged and used to determine the material stiffness.

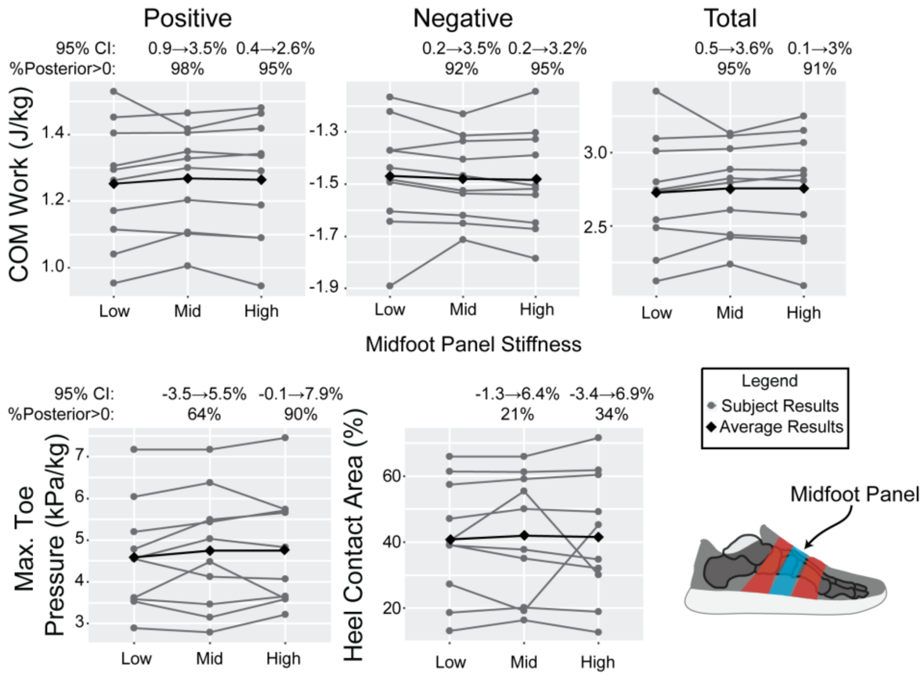

Figure 1. Changes in centre-of-mass (COM) work and plantar pressure with different midfoot panel stiffness while running at 3.0 m/s. Presented above the "Mid" and "High" stiffness are the Bayesian statistics denoting differences from the "Low" stiffness: 95% credible intervals (CI) and the percent of the posterior above zero (%Posterior>0). The plots indicate subject averages (dots) and study averages (diamonds). Bottom right is a depiction of the wrap on the medial side of the shoe and the midfoot panel which differed in stiffness.

We evaluated biomechanical metrics that are associated with running performance and footwear fit. We first computed the time-continuous centre-of-mass (COM) power from the ground reaction forces using the individual limbs method (Donelan et al., 2002). We then integrated under the positive and negative portions of the curve for the respective work metrics during the stance phase. Running steps were segmented based on the ground reaction force. The total COM work was the summed absolute value of the positive and negative COM work. We evaluated peak toe pressure and heel contact area during the second half of the stride as footwear fit metrics (Dobson et al., 2018; Hagen & Hennig, 2009; Honert et al., 2023). Running steps for pressure were segmented based on the summed pressure of the insole.

We performed a series of statistical tests to determine differences between the low stiffness condition and the other conditions along with relationships between outcomes (RStudio, v4.1.2). First, all step-by-step outcomes were converted to z-scores by each individual prior to statistical tests. We used a Bayesian linear mixed model to estimate differences in plantar pressure and COM work. The model fits an independent intercept for each subject and an independent slope for each stiffness condition. The prior for each model was centred on zero with a standard deviation of one to not bias the posterior outcome. The percent of the posterior greater than zero and 95% credible intervals (95% CI) are presented for each metric. Lastly, we evaluated the relationships between total COM work and heel contact area and peak toe pressure using two separate linear models and evaluating goodness of fit of each model separately. Average data from each subject and condition were used as linear model inputs.

RESULTS: Increasing the midfoot panel stiffness from 2 N/mm (Low) to 14 N/mm (Mid) or 23 N/mm (High) resulted in an increase in magnitude in positive (Mid 95% CI: 0.9 to 3.5%, High 95% CI: 0.4 to 2.6%, Figure 1) and negative COM work (Mid 95% CI: 0.2 to 3.5%, High 95% CI: 0.2 to 3.2%) on average of ~1 J. Increasing the panel stiffness from Low to Mid or High also resulted in an average increase of ~2 J in total COM work (Mid 95% CI: 0.5 to 3.6%, High 95% CI: 0.1 to 3.0%). There were relatively little differences in plantar pressure metrics between the midfoot panel stiffness conditions (see Figure 1 for 95% CI); however, peak toe pressure did increase between the Low and High midfoot panel stiffness on average by 7 kPa (95% CI: -0.1 to 7.9%). Athletes rated the overall fit of the Low the highest (average: 8/10) followed by Mid (average: 7.75/10), and High stiffness (average: 7/10).

There were weak relationships between plantar pressure and total COM work. The linear model regressing total COM work on peak toe pressure showed a goodness of fit of $R^2 = 0.205$ with increasing peak toe pressure resulting in higher COM work. The linear model regressing total COM work on heel contact area showed a goodness of fit of $R^2 = 0.093$ with increasing heel contact area resulting in lower COM work.

DISCUSSION: This is the first study to systematically target footwear upper stiffness around bony prominences in the foot. We found that having a stretchy midfoot panel with a stiffer instep and forefoot panel improved running performance. We also observed improvements in subjective fit and objective fit metrics such as reduced peak toe pressures, which has been interpreted as a reduction in the amount of “toe clawing” (Dobson et al., 2018).

In this study, we evaluated running performance with COM work. Specifically, we observed with the least stiff midfoot panel (2 N/mm) reduced the COM work to run at a set speed. The COM work is contributed mainly from the ankle joint during running (with contributions from the knee and hip, Riddick & Kuo, 2016). Reducing the work from the ankle in footwear interventions (such as the Vaporfly, Hoogkamer et al., 2019) has resulted in large changes in running performance (Hoogkamer et al., 2019).

We also sought to understand if plantar pressure metrics are associated with performance, and we observed a weak trend ($R^2 = 0.205$) between peak toe pressure and COM work. The fact that peak toe pressure explained 20% of the variance in total COM work is a reasonable – albeit low – proportion. This is likely due to several additional factors contributing to the amount of COM work (e.g. ankle push-off) or could be due to a small sample size of runners in our study (N=10). If we evaluate all runners (N = 36) across the eight different studies from our lab in 2023 (Figure 2),

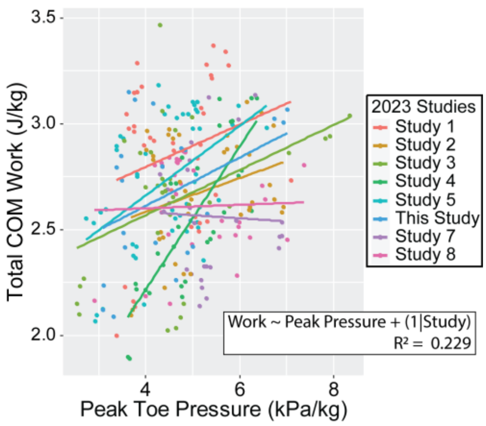

Figure 2. Relationships between peak toe pressure and total COM work for athletes running at 3 m/s. Dots are averages for each participant and shoe (n = 262). Lines represent a linear fit for each study.

peak toe pressure explains about 25% of the variance in total COM work. This improvement in model fit demonstrates that peak toe pressure is associated with running performance and is a metric that can be used outside-the-lab to understand both fit and performance. While this metric does not explain all of the variance in COM Work, it can be used with other sensors such as inertial measurement units that can determine running speed (Honert et al., 2023). This study specifically targeted changes in the stiffness in one panel over the cuneiforms and one athletic activity. Such changes could be implemented in the future through targeted changes in footwear uppers through application of thermoplastic polyurethane or through use of a BOA wrap, similar to this study. Further research is needed to understand if adding and changing panel stiffness around the metatarsophalangeal joint can improve performance. It is also not known how such stiffness changes affect overground running, jumping, or cutting. Future research could focus on evaluated these different effects using forward simulations.

CONCLUSION: Running performance and footwear fit was improved with matching footwear upper material properties with the underlying foot structure. We matched these material properties by using a stretchy material over the cuneiforms with a stiffer material across the metatarsals and talus. Through this investigation into shoe uppers, we also found that a metric of footwear fit such as peak toe pressure is associated with running performance. Establishing such relationships can enable researchers to utilize wearable metrics outside-the-lab.

REFERENCES

Dobson, J. A., Riddiford-Harland, D. L., & Steele, J. R. (2018). Effects of wearing gumboots and leather lace-up work boots on plantar loading when walking on a simulated underground coal mine surface. *Footwear Science*, *10*(3), 139–148. https://doi.org/10.1080/19424280.2018.1486461

Donelan, J. M., Kram, R., & Kuo, A. D. (2002). Simultaneous positive and negative external mechanical work in human walking. *Journal of Biomechanics*, *35*(1), 117–124. https://doi.org/10.1016/S0021-9290(01)00169-5

Hagen, M., & Hennig, E. M. (2009). Effects of different shoe-lacing patterns on the biomechanics of running shoes. *Journal of Sports Sciences*, *27*(3), 267–275. https://doi.org/10.1080/02640410802482425

Hoitz, F., Mohr, M., Asmussen, M., Lam, W.-K., Nigg, S., & Nigg, B. (2020). The effects of systematically altered footwear features on biomechanics, injury, performance, and preference in runners of different skill level: A systematic review. *Footwear Science*, *0*(0), 1–23. https://doi.org/10.1080/19424280.2020.1773936

Honert, E. C., Harrison, K., & Feeney, D. (2023). Evaluating footwear “in the wild”: Examining wrap and lace trail shoe closures during trail running. *Frontiers in Sports and Active Living*, *4*. https://www.frontiersin.org/articles/10.3389/fspor.2022.1076609

Hoogkamer, W., Kipp, S., Frank, J. H., Farina, E. M., Luo, G., & Kram, R. (2018). A Comparison of the Energetic Cost of Running in Marathon Racing Shoes. *Sports Medicine*, *48*(4), 1009–1019. https://doi.org/10.1007/s40279-017-0811-2

Hoogkamer, W., Kipp, S., & Kram, R. (2019). The Biomechanics of Competitive Male Runners in Three Marathon Racing Shoes: A Randomized Crossover Study. *Sports Medicine*, *49*(1), 133–143. https://doi.org/10.1007/s40279-018-1024-z

Luftglass, A. R., Feeney, D. F., & Queen, R. M. (2023). The effect of upper panel stiffness on biomechanical performance in athletic footwear. *Footwear Science*, *15*(3), 193–202. https://doi.org/10.1080/19424280.2023.2184874

Pryhoda, M., Wathen, R., Dicharry, J., Shelburne, K., & Davidson, B. (2020). *Alternative shoe closure designs alter biomechanical performance during agility-based movements* [Preprint]. SportRxiv. https://doi.org/10.31236/osf.io/5fr9t

Riddick, R. C., & Kuo, A. D. (2016). Soft tissues store and return mechanical energy in human running. *Journal of Biomechanics*, *49*(3), 436–441. https://doi.org/10.1016/j.jbiomech.2016.01.001

Sengeh, D. M., & Herr, H. (2013). A Variable-Impedance Prosthetic Socket for a Transtibial Amputee Designed from Magnetic Resonance Imaging Data. *JPO: Journal of Prosthetics and Orthotics*, *25*(3), 129–137. https://doi.org/10.1097/JPO.0b013e31829be19c

Subramanium, A., Honert, E. C., Cigoja, S., & Nigg, B. M. (2021). The effects of shoe upper construction on mechanical ankle joint work during lateral shuffle movements. *Journal of Sports Sciences*, *0*(0), 1–9. https://doi.org/10.1080/02640414.2021.1898174