INCREASED FOREFOOT ENERGY RETURN OF FOOTWEAR IMPROVES METABOLIC ENERGY EXPENDITURE

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The purpose of this study was to determine how systematically increasing the energy return in the forefoot of running footwear impacts energy expenditure of running. For this, 13 participants ran on a treadmill at a submaximal speed, in three shoe conditions differing only in their mechanical properties of the midsole foam, allowing an energy return of 11 J, 12 J, and 13 J, respectively. Running with a 13 J energy return improved energy expenditure compared to the condition with 11 J (2.03%; $p = 0.026$). The 12 J condition did not significantly differ from the others. These findings suggest that a 2 J increase in forefoot energy return from footwear improves energy expenditure of running, potentially contributing to recent world records in long-distance running.

KEYWORDS: running, economy, footwear, shoe, foam, energy return.

INTRODUCTION: Recent innovations in advanced footwear technologies (AFT) led to many world records broken in elite long-distance running. One of the most prominent records was set during the Berlin marathon in September 2023, when Tigist Assefa ran 2:11:53 hr:min:s and with that obliterated the previous fastest women's marathon time by more than two minutes. It has been argued that significant amounts of such performance improvements can be attributed to different properties and benefits of AFTs over more traditional running footwear (Hoogkamer et al., 2018; Burns & Tam, 2019). In general, the advances in shoe technology themselves have been designed to maximize running economy while minimizing energy loss and consist of a curved stiffening element and a high midsole stack height made of compliant, resilient, and lightweight foam. One possible mechanism contributing to the improved performance when running in AFTs could be specifically the increased energy return in the forefoot. Advancements in foam developments have allowed greater elastic energy to be stored and returned from the foam built into the forefoot of footwear, as determined through standardized mechanical testing. Previously, Worobets et al. (2014) have established that an increased energy return into running footwear enhances running economy (RE), yielding improvements of 1.0% on a treadmill and 1.2% in overground running when comparing shoes of different levels of energy return. It should be considered, however, that the construction of racing footwear has significantly changed in recent years, now incorporating curved stiffening elements such as plates or rods to provide greater longitudinal bending stiffness. Furthermore, the energy return of the footwear conditions used by Worobets et al. (2014) was <10 J, which is low when compared to AFTs that are nowadays used in elite long-distance running. For this reason, it is unknown how transferrable the previously reported benefits of ~1% are to AFTs, and therefore it is necessary to re-examine the question of energy return on RE with state-of-the-art racing footwear. Furthermore, understanding the specific energy return threshold, at which it significantly impacts running performance, could provide athletes with data-driven guidance, enabling them to make more informed choices for optimal performance enhancement. This insight would also be invaluable for the sportswear industry in tailoring product development to meet the precise needs of runners. Therefore, the purpose of this study was to investigate if metabolic energy expenditure can be improved during treadmill running when the energy return is systematically altered in the forefoot region of AFTs. It was hypothesized that increasing the energy return will result in improved metabolic energy expenditure based on previous research done using non-AFT shoes (Worobets et al., 2014).

METHODS: Thirteen (11 male and 2 female, age: 33.2 ± 4.3 yrs, height: 176.9 ± 4.7 cm, mass: 68.9 ± 6.6 kg) healthy recreational runners provided informed consent before participating in this study, where they ran on a treadmill (gaitway 3D, h/p/cosmos sports & medical gmbh, Nussdorf-Traunstein, GER) in three shoe conditions providing different amounts of energy return (i.e., Low, Mid, High) at a submaximal speed for 6 minutes, respectively. The shoe conditions were identical in visuals and manufacturing but differed only in the material used in the midsole. By changing the material and its properties, systematic differences in energy return in the forefoot area of the shoes were achieved. Standardized mechanical testing was performed using a hydraulic linear-torsion testing machine (Model 8502, Instron, Norwood, USA) to determine the energy return of the shoe conditions. For this, a forefoot last was attached to the machine, which applied a vertical, compressive force to the forefoot region of the shoes. The machine, programmed to achieve a target force of 2000 N and measure the last's displacement, calculated the energy return (in Joules) from the area under the unloading segment of the force-displacement curve. Mechanical testing showed that Low, Mid, and High returned 11.0 J, 12.2 J, and 13.1 J of energy, respectively. Prior to running in the three conditions, participants performed a 6-min warm-up and familiarization trial in a standardized shoe. Before the familiarization trial, the researchers applied shoe covers over the participants' footwear as these were used to blind the subjects to the conditions during the experiment. During the familiarization, running speed was selected based on self-reported current half-marathon/marathon personal bests and, if needed, adjusted so that the respiratory exchange ratio (i.e., the ratio of rates of oxygen consumption and carbon dioxide production) would remain below 1 during the testing trials. Average running speed was 3.3 ± 0.3 m/s (i.e., 5:02 min/km). For the experimental trials, the order of shoe conditions participants ran in were balance-randomised, so that the number of occurrences of each order was similar. After the familiarisation trial, participants were given a 6-min break during which runners were blindfolded while researchers removed the current shoes and put on the subsequent pair again with the covers. Additionally, small masses (TECPO, Remscheid, GER) were inserted in between the two layers of the shoe covers to weight-normalize the footwear conditions; in the end, each shoe had a mass of 230 g. Energy expenditure (W/kg) was measured based on indirect calorimetry using breath-by-breath rates of oxygen consumption and carbon dioxide production captured with a metabolic cart using the Péronnet and Massicotte equation (Péronnet & Massicotte, 1991) (METALYZER 3B, CORTEX Biophysik GmbH, Leipzig, GER). Breath-by-breath metabolic data was cleaned by removing outlying data points that were more than two standard deviations away from the mean of a seven-breath window and smoothed by taking a moving seven-breath average (Knopp et al., 2023). Therefore, the resultant steady-state value was taken over a 120-second window from minute 3:30 to 5:30 of testing. The normality of the outcome variables was tested using the Shapiro-Wilk test. As the assumption of a normal distribution was violated, the Friedman test was used to test for effects of energy return on metabolic energy expenditure. Multiple Wilcoxon signed-rank tests were then used for pairwise comparisons between shoe conditions. The significance level α was set to 0.05.

RESULTS: Statistical analysis revealed significant footwear main effects on energy expenditure during submaximal running ($p = 0.036$) with the High energy return condition being significantly different to the Low condition ($p = 0.026$), while the Mid energy return midsole was neither significantly different to the Low ($p = 0.216$) or the High condition ($p = 0.497$) (Figure 1). Given that not all subjects ran at the same speed, relative differences were also examined with the Mid energy return condition at 11 J showing a non-significant 0.95 ± 3.13% benefit in energy expenditure compared to the Low midsole at 10 J, while the High midsole at 12 J showed a benefit of 2.03 ± 2.73%. Similar results were shown for all analyzed metabolic variables we examined including running economy (mL/kg/min) (High: 43.0 ± 4.4; Mid: 43.5 ± 4.4; Low: 43.8 ± 4.3 mL/kg/min), and the oxygen cost of transport also taking distance covered into consideration (mL/kg/km) (High: 216.8 ± 19.2; Mid: 219.2 ± 17.8; Low: 220.8 ± 19.0 mL/kg/km).

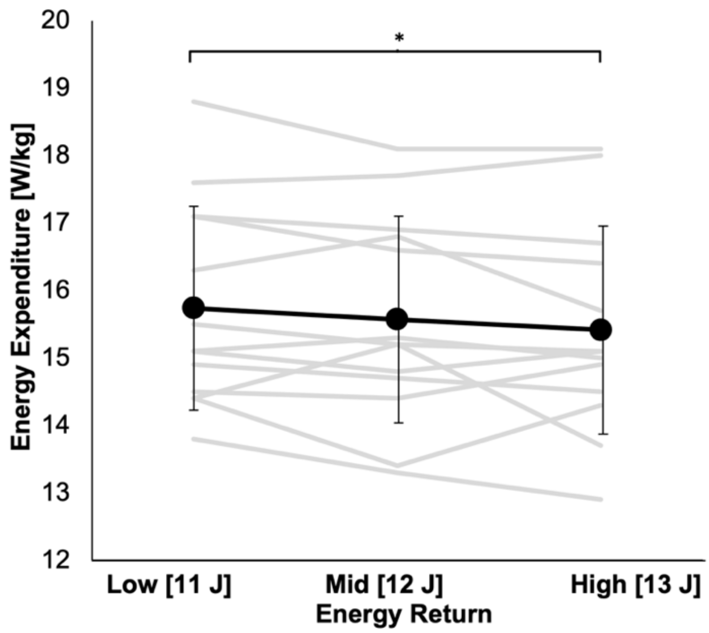

Figure 1: Effect of energy return [J] of the midsole material on running metabolic energy expenditure [W/kg], shown as the different subjects (grey line) and the combined average ± standard deviation (black line). *Indicates significant differences ($p < 0.05$).

DISCUSSION: Increasing the forefoot energy return of AFTs by 2 J offers a significant performance benefit by decreasing the energy expenditure by 2% at that given speed. It has been shown that a 2% decrease in energy expenditure can be translated to a ~1.5% improvement in running time (Hoogkamer et al., 2016). Before Tigist Assefa broke the women's marathon world record in Berlin in 2023, the previous fastest time was at 2:14:04 set by Brigid Kosgei. A 1.5% improvement from 2:14:04 would translate to a total of 120 seconds. Tigist Assefa ran 131 seconds faster to establish her astonishing world record time of 2:11:53. This means that the performance improvement observed during the race is very comparable in magnitude to theoretical improvements one could obtain through a 2 J increase in energy return of footwear, as shown in this study. Therefore, it could be speculated that the recent improvements in marathon performance (e.g., the women's world record set during the Berlin marathon in September 2023) can at least partially be attributed to the advancements in footwear technologies. Although a 2 J increase in energy return caused a significant reduction in energy expenditure, a 1 J increase was not large enough to elicit a statistically significant improvement. Given the sample size of 13 runners, we speculate that a larger number of participants would have been required to find statistically significant differences between shoe conditions with this specific test method. While Worobets et al. (2014) did not report the energy return of the tested shoes, based on the presented force-displacement curves, estimated peak forces and maximum deformations, and energy loss (i.e., hysteresis), we can estimate their control condition to have returned 4.7 J, while the soft and resilient condition returned 6.7 J. Their treadmill results found "only" a 1% running economy benefit with this 2 J difference in energy return between conditions. This suggests that innovative midsole foam solutions that are found in current versions of AFTs are outperforming previous generations of running shoe midsole materials. Overall research examining the performance benefit of AFTs in amateur runners in a laboratory setting found an average 4.4% improvement in running economy (mL/kg/min) compared to traditional racing flats (Knopp et al., 2023). Different components within these AFTs could be influencing this overall improvement. Previous work has addressed particularly the increased longitudinal bending stiffness and reduced shoe mass. Incorporating a carbon-fiber stiffening element into the midsole increased the longitudinal bending stiffness and has been shown to reduce the energetic cost of running by about 1% (Roy & Stefanyshyn, 2006). The innovations in midsole foams have allowed the volume of the midsole to increase while remaining lightweight. This is of particular importance as Frederick (1984) showed that a 100 g reduction in shoe mass led to an average 1% improvement in oxygen uptake during running. While the exact mechanisms of how AFTs affect performance continue to be debated, this research shows that the increased energy return could be one variable contributing to the recent surge of world records in long distance running events. Finally, some limitations to this work need to be acknowledged. Unfortunately, only two female participants were able to be recruited for this experiment. A larger cohort of female subjects would have allowed for comparisons between sexes to confirm similar effects of energy return on energetic expenditure during running. Furthermore, the focus of this study was specifically on systematically altering the energy return of the midsole while weight-matching across the conditions. We acknowledge, however, that in the attempt to create these systematic midsoles, other properties, such as force-displacement behaviors, maximum deformation, etc., may have also been changed and were not controlled for. Lastly, we acknowledge the widespread variation shown in the individual data that aligns with similar studies examining the effect of AFT on running performance (Knopp et al., 2023) exaggerated here by varying speeds in the protocol given the different skill levels of the participants at the time of testing. Due to the within-subject design of this experiment, the between-subject speed variations do not affect the overall interpretations of the results.

CONCLUSION: To our knowledge, this is the first study examining specifically the energy return component of novel AFT foams returning more than 10 J during submaximal running. This study has shown that increasing the forefoot energy return of the midsole by more than 2 J leads to a benefit in running performance shown by a significant 2% decrease in energy expenditure in the 13 J energy return condition compared to the 11 J condition. Therefore, increased energy return of racing footwear can be one of the main contributors to the most recent women's world record set during the Berlin marathon in 2023.

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