THE EFFECT OF FOOTWEAR FIT ON MOVEMENT COMPLEXITY IN TRAIL RUNNING

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In trail running athletes must adapt their movement patterns to navigate obstacles in their path. Sample entropy is a method to evaluate an athlete's flexibility to alter their movement from stride to stride. The purpose of this study was to examine the effects of running speed, duration, terrain, sex, and footwear on movement complexity in trail runners. Thirty trail runners (15 female) ran a trail loop in two shoes: a lace shoe and a wrap shoe. We used linear mixed effects models to examine the effects of independent variables on sample entropy of foot accelerations. More technical terrain, faster running speed, being early in the run (vs. the end of the run), female sex and the wrap shoe were associated with greater complexity. A wrap shoe designed to better conform to the foot may offer improvements in movement complexity associated with better running performance and absence of injury.

KEYWORDS: sample entropy, sex, performance, regularity, fit.

INTRODUCTION: In trail running, athletes must navigate constantly changing terrain. However, understanding runner's ability to adapt their movement patterns over such terrain has received little attention. One approach to assess this ability is sample entropy, a method to quantify the complexity of an athlete's movement patterns (Lamoth et al., 2009). This complexity is defined as how well a time series can be predicted by itself – i.e. how similar is a stride to future strides. Low complexity may be indicative of maladaptive physiological functioning (Lipsitz & Goldberger, 1992). Applied to trail running, low entropy could indicate insufficient flexibility in movement patterns to adapt to changes or obstacles in the environment. To date, greater sample entropy has been related to running economy, and absence of pain or injury (Quirino et al., 2021; Schütte, Sackey, et al., 2018). However, most of the research regarding movement complexity in runners has been done in lab environments, or on smooth outdoor running surfaces. There is little research on entropy in varying technical terrain.
In addition, we currently lack understanding of how footwear affects movement complexity in runners. A better fitting shoe could enhance tactile feedback by providing greater contact area between the foot and the shoe, ultimately improving an athlete's ability to respond to changing conditions underfoot. Currently, there are commercially available trail running shoes designed to better conform to athletes' feet using a flexible wrap over the top of the foot, activated by a dial and lace system. These footwear have been shown to improve trail running performance compared to traditional lace footwear (Honert et al., 2023). The purpose of this study was to understand the effects of footwear fit, terrain, and running duration on movement complexity in male and female trail runners.

METHODS: For this study, we analysed data from a previously published manuscript (Honert et al., 2023). Thirty trail runners (15 female) ran a 1.6 km loop five times. The trail consisted of an uphill section, a technical flat section, and a downhill section. The data collections were conducted only in dry conditions. The first loop was a familiarization run. The next four loops were run in two different pairs of test shoes, in a randomized, counterbalanced order: Shoe A, Shoe B, Shoe B, Shoe A. The two shoes were identical except for the uppers (La Sportiva Cyklon; Figure 1). One shoe used a traditional lace closure system. The other used a wrap over top of the foot, which was activated by a dial system (BOA Fit System, Denver, USA). An IMU was attached to the heel counter of each shoe during running (±16g and ±2000°/sec at 1125 Hz with 16-bit sensitivity, ±200g at 1600 Hz with 13-bit sensitivity, IMeasureU, Denver, USA). Athletes also wore a GPS watch (Suunto, Vantaa, Finland). Athletes were instructed to run each loop at a moderate pace, emphasizing consistency in running pace across all laps.
Data processing: Data from each loop were segmented into the uphill, flat and downhill sections using timestamps from the GPS data. Heel strikes were identified based on the peak jerk of the acceleration signal. Foot flat of each step was identified as a timeframe when the

angular velocity signal from the gyroscope was approximately zero. Foot flat was used to rotate the accelerometer signal such that the gravity vector aligned with the vertical axis of the accelerometer. Further, the angular orientation of the foot throughout the stride was estimated by integrating the gyroscope signal. Signal noise was accounted for with a linear correction. This orientation was used to correct the accelerometer data to be oriented in the global space, rather than the local coordinate system of the foot. Sample entropy was calculated using 30 consecutive strides in the middle of each segment, using a series length (m) of 2, and a tolerance (r) of 0.2 times the standard deviation of the time series (Yentes et al., 2013). The effects of terrain (i.e trail segment), running speed, trial number (i.e. early vs. later in the run), sex, footwear condition and the interaction of sex by footwear condition, were estimated using linear mixed effects models, with subject included as a random effect. If there were any fixed effects for which the p-value was >0.1, the effect with the largest p-value was removed, until all effects had a p-value <0.1.

Figure 1: Study footwear. Left: Wrap closure. Right: Traditional lace closure.

RESULTS: Running terrain influenced movement complexity in all three directions. The uphill and flat technical segments had greater movement complexity compared to the relatively smooth downhill section (p<0.006, Table 1) with the exception of the flat terrain in the anteroposterior direction (p=0.14). Running speed had limited effects on movement complexity. It was only retained in the model for sample entropy in the antero-posterior direction; at faster paces, trail runners tended to have greater complexity (p=0.07). Regarding run duration, trail runners demonstrated a reduction in movement complexity in the mediolateral direction as the data collection progressed (p=0.02). In comparison of males and females, we found that males tended to display less complexity in the mediolateral direction than females (p=0.08). The wrap shoe was associated with greater sample entropy in all three directions compared to the lace shoe (p<0.04). There were no Shoe*Sex interaction effects.

Table 1. Coefficient estimates (Est) of linear mixed models for sample entropy.

Direction	**Trail Segment**		**Trial Number**	**Speed**	**Shoe (Wrap)**	**Sex (Male)**	**Shoe* Sex**
	Flat	**Uphill**					
Vertical	Est=0.006 p=<0.001	Est=0.016 p=<0.001	N/A	N/A	Est=0.005 p=<0.001	N/A	N/A
Medio-lateral	Est=0.01 p=<0.001	Est=0.03 p=<0.001	Est=-0.002 p=0.02	N/A	Est=0.005 p=0.007	Est=-0.02 p=0.08	N/A
Antero-posterior	Est=0.004 p=0.14	Est=0.007 p=0.006	N/A	Est=0.006 p=0.07	Wrap: Est=0.003 p=0.04	N/A	N/A

DISCUSSION: This is the first study to examine running complexity in a technical train environment. Technicity elicited greater complexity, indicating that more challenging terrain requires greater flexibility in movement patterns. Previously, a comparison of running on a concrete road surface vs. a wood chip trail found no significant differences in sample entropy of trunk accelerations (Schütte et al., 2016). The larger obstacles in the trail used for this study likely necessitated more pronounced adaptations in movement pattern. Faster running speed was also associated with greater complexity. It is likely that greater complexity reflects a better ability to adapt to challenging terrain, and thus enhances running performance.

On the other hand, complexity diminished as the run progressed. In contrast to our results, sample entropy in the anteroposterior direction increased in runners during treadmill running (Schütte et al., 2015). Running on a treadmill presents little need for adaptations in movement pattern due to the environment. In that case, an increase in complexity may reflect a more disorganized movement pattern that does not benefit a runner. Trail running presents more demands in the mediolateral direction to navigate obstacles, thus a loss of complexity may represent a maladaptive change. In fact, runners with a history of medial tibial stress syndrome exhibit a loss of movement complexity with fatigue (Schütte, Seerden, et al., 2018).

It is not surprising that females displayed greater complexity in the mediolateral direction. Similarly, Schutte et al. (Schütte, Sackey, et al., 2018) found that sample entropy of the trunk in the mediolateral direction was lower in males than females. Females display larger range of motion in the frontal plane during running, which may allow for greater movement complexity (Luz et al., 2022).

Given the association of movement complexity with injury and performance, it is important to consider how athletes might be able to improve this characteristic. Given the increase in complexity with the wrap shoe seen in both males and females, we propose that enhancing sensory feedback to an athlete would allow them to better adapt to a changing environment. The wrap shoe was previously shown to increase contact area between an athlete's foot and the shoe – in particular at the heel (Honert et al., 2023). It is possible that improved contact area creates pressure that provides a type of haptic feedback, providing an athlete more information about their foot position relative to the surface underfoot. In support of this theory, wrapping the foot/ankle with tape improves balance and proprioception (Fazeli et al., 2018; Robbins et al., 1995). As noted above, greater sample entropy in the anteroposterior and mediolateral directions were associated with greater running speed and shorter run duration, respectively. A better fitting shoe may help to improve performance in part via improved adaptability to the terrain and offset changes in movement complexity associated with fatigue. In a previous study, greater sample entropy of trunk acceleration in the mediolateral direction was an important predictor of better running economy (Schütte, Sackey, et al., 2018), which supports a performance benefit of greater mediolateral complexity. Further, runners with no history of injury display greater movement complexity in lower limb joint kinematics than asymptomatic runners with a history of injury (Quirino et al., 2021). In fact, a consistent relationship between injury and low movement complexity is seen in the literature (Armitano-Lago et al., 2023; Bacon et al., 2022; van de Ven et al., 2023). Our findings indicate that better fitting footwear may contribute to healthier movement patterns.

CONCLUSION: This study demonstrates that movement complexity is an important attribute in trail running and that flexible movement patterns are used by runners to navigate technical terrain. Further, greater complexity is associated with faster running speed, while reduced complexity is associated with longer running duration, and may be indicative of fatigue and impaired ability to adapt to obstacles in a trail running environment. Importantly, we identified a potential method to improve movement complexity via better fitting footwear. Footwear designed to better wrap the foot enhanced movement complexity, which has been associated with better running economy, and absence of pain and injury. Footwear fit may be an important consideration for health and performance in trail running. Further research is needed to directly evaluate the role of movement complexity in running economy and injury in trail running.

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