Full length article

Local dynamic stability of the lower extremity in novice and trained runners while running intraditional and minimal footwear

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ABSTRACT

Background: Understanding how footwear cushioning influences movement stability may be helpful in reducing injuries related to repetitive loading. Research Question: The purpose of this study was to identify the relationship between running experience and midsole cushioning on local dynamic stability of the ankle, knee and hip.
Methods: Twenty-four trained and novice runners were recruited to run on a treadmill for five minutes at the same relative intensity. Midsole thickness (thick/thin) and stiffness (soft / hard) were manipulated yielding four unique conditions. Lyapunov exponents were estimated using the Wolf algorithm from sagittal ankle, knee and hip kinematics.
Results: Trained runners had increased movement stability in all shoe conditions compared to their novice counterparts. Midsole thickness and stiffness, overall, did not affect movement stability within each of the running groups. Novice runners displayed decreased movement stability at the hip while running in the thick/ soft running shoes. It was found that running experience has a greater influence on movement stability in the lower limbs compared to the midsole characteristics that were manipulated in this experiment. The hip was most stable followed by the knee and the ankle highlighting decreased stability in distal joints.
Conclusions: It appears that midsole design within current design ranges do not have the ability to influence movement stability.

1. Introduction

Alternating one's loading during running variability by manipulating footwear characteristics could be beneficial for runners [1]. It has been shown that stride interval variability is greater in novice runners compared to their trained runner counterparts [2]. These findings show how important running experience is in refining cyclical movement patterns. From a running economy perspective, the changes that occur over time with training serve to benefit the athlete and make them more economical, leading one to believe that reduced variability is favourable in running from a metabolic perspective. Running on uneven terrain has been shown to increase running economy by 5% [3]. However, there is evidence that reduced variability in running is linked to risk of injury [4]. From an injury perspective, it has been suggested that when tissue fails, the rate of tissue remodelling is slower than the rate of tissue damage [5]. In distance running, where repetitive stress is applied, the knee is the most injured joint in the body [6]. Furthermore, runners with a history of patellofemoral pain syndrome (PFPS) have been shown to have less variability in continuous relative phase

(segment coupling) compared to runners with no history of injury [4]. From these examples one may believe that too little variability may be linked to increased risk of overuse injuries. It becomes apparent that there is a trade off between too much and too little variability while running, rather, a healthy range of variability exists based on a number of factors [7].

Aside from running experience, midsole characteristics are important in connecting a runner to the ground. Variability in running may be related to the quality of afferent feedback from the plantar surface of the foot. Additionally, altering midsole properties has the ability to change this afferent feedback during single legged balance [8]. It is hypothesized that midsole material acts to degrade the quality of afferent information that would otherwise be gained directly from ground contact. Furthermore, previous work has found a relationship between severity of impacts and perceived comfort in different cushioning conditions [9,10]. Shoes with softer midsoles have been shown to attenuate vertical loading rates [11]. The amount of variability while running barefoot and shod has been assessed previously with findings indicating that variability is increased while running barefoot both in

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kinematics [12], and kinetics [13]. It is suggested that variability increases while barefoot to decrease the risk of injury by preventing overloading under the heel [14]. The cited work has utilized different methodologies to understand movement variability including linear measures such as standard deviations and long term correlations. Understanding how the control of running is influenced by experience and footwear may not be fully captured with the use of linear methods as sequential strides are inherently related. It is still unknown how running stability is influenced between novice and trained runners and the potential for each group to sense different cushioning properties, which may influence movement stability.

This work seeks to evaluate differences in local dynamic stability between trained and novice runners at a joint level, for the ankle knee and hip. Understanding the differences between groups of varying experience, and investigating how groups respond to footwear with differing midsole characteristics can aid in recommending footwear that is tailored to someone's running experience. It was hypothesized that local dynamic stability would be decreased in novice runners in comparison to trained runners due to lack of experience and training. It was also hypothesized that firmer underfoot material will decrease local dynamic stability for all participants while softer underfoot material will increase local dynamic stability due to the perceived impact across shoe conditions and the ability to change one's landing patterns over the running trial.

2. Methods

2.1. Participants

Twenty four male participants were recruited to participate in this study. Novice runner and trained runner groups were created with each group consisting of twelve participants. Selection criteria for the groups were as follows: novice runners ran less than a total of 10 km within the past year [15], while trained runners ran a minimum of 30 km per week on average. All participants had to be free from injury within the past three months and have had no experience using any type of product that had been marketed as a barefoot / minimal running shoe. This study received ethics clearance from the University of Waterloo's Office of Research Ethics review board prior to participant recruitment.

2.2. Footwear

Four shoe conditions were included in this study (Figure 1). Both the midsole stiffness and thickness were manipulated to differentiate minimal shoes from traditional shoes. The two levels of midsole stiffness that were used included 40 Asker C (Soft) and 70 Asker C (Hard). Two variables that are manipulated with footwear construction include stack height and heel to toe drop. Stack height is defined as the thickness of the midsole whereas heel to toe off set is the difference

Fig. 1. Four different shoe conditions were used based on altering midsole thickness and stiffness.

between the heel region's height and the forefoot regions height. For the minimal shoes, stack height was 13 mm and the heel to toe drop was 4 mm. For the traditional shoes, stack height was 20 mm and the heel to toe drop was 12 mm.

2.3. Experimental setup

Lower body kinematics were collected using an Optotrak motion capture system (NDI, Waterloo, ON, Canada) from rigid bodies mounted on the pelvis, right thigh, shank and foot, sampled at 100 Hz. Participants wore a heart rate monitor throughout the data collection to allow for a similar work rate between the trained and novice running groups (Forerunner 405, Garmin Ltd., Olathe, KS, U.S.A.).

2.4. Experimental protocol

Rating of Perceived Exertion (RPE) was used as a guideline to control for the running intensity between novice and trained runners [16]. Participants were given time to warm up on the treadmill and were instructed to increase the speed until they reached an RPE score equal to '3' or a moderate effort. Since the level of running expertise was different between groups, preferred running speed was different while the relative intensity between groups was normalized [17]. For each of the four shoe conditions, participants ran for four minutes on a treadmill at the pre-determined speed. Shoe order was randomized and rest was given between all bouts of running.

2.5. Data analysis

Raw marker trajectories were filtered using a 2nd order dual pass Butterworth filter with a cutoff frequency of 15 Hz. Sagittal relative joint angles for the ankle, knee and hip were calculated using Visual 3D V 4.85.0 (C-Motion Inc., Germantown, MD).

2.6. LyE estimation

Local dynamic stability from kinematic data was estimated from the largest Lyapunov exponent (LyE). The LyE represents the maximum rate of divergence of nearby trajectories in state space. Before estimation of the LyE, the original time series data were reconstructed in state space (Figure 2). The reconstructed state space vector was composed of multiple (M) time delayed copies (τ) of the original time series (x(t)), where M is the appropriate number of dimensions and τ was the time delay to reconstruct the attractor dynamics (Eq. (1)).

$$y(t) = [x(t), \ x(t + \tau), ..., (t + (M - 1)\tau)] \tag{1}$$

The reconstruction lag (τ) was determined from the average mutual information algorithm [18]. The reconstruction lag was selected from the first local minimum of the average mutual information algorithm.

Embedding dimension (M) was determined from the global false nearest neighbours algorithm [18]. The appropriate embedding dimension was equal to the point at which the percentage of false nearest neighbours drops to zero.

The largest LyE represents the maximum rate of divergence between nearest neighbours in state space. Once nearest neighbours were found, the distance between them was calculated (d_t), the algorithm stepped forward (k) data points and the distance was recalculated ($d_{t'}$). The LyE is the average rate of divergence or convergence from the running average of the differences in distances (Eq. (2)).

$$LyE = \frac{log_2\left(\frac{d_{t'}}{d_t}\right)}{k} \tag{2}$$

Where d_t is the initial distance between nearest neighbours, $d_{t'}$ is the final distance between nearest neighbours and k is the number of time steps taken between the first and second point. The value of k was set to
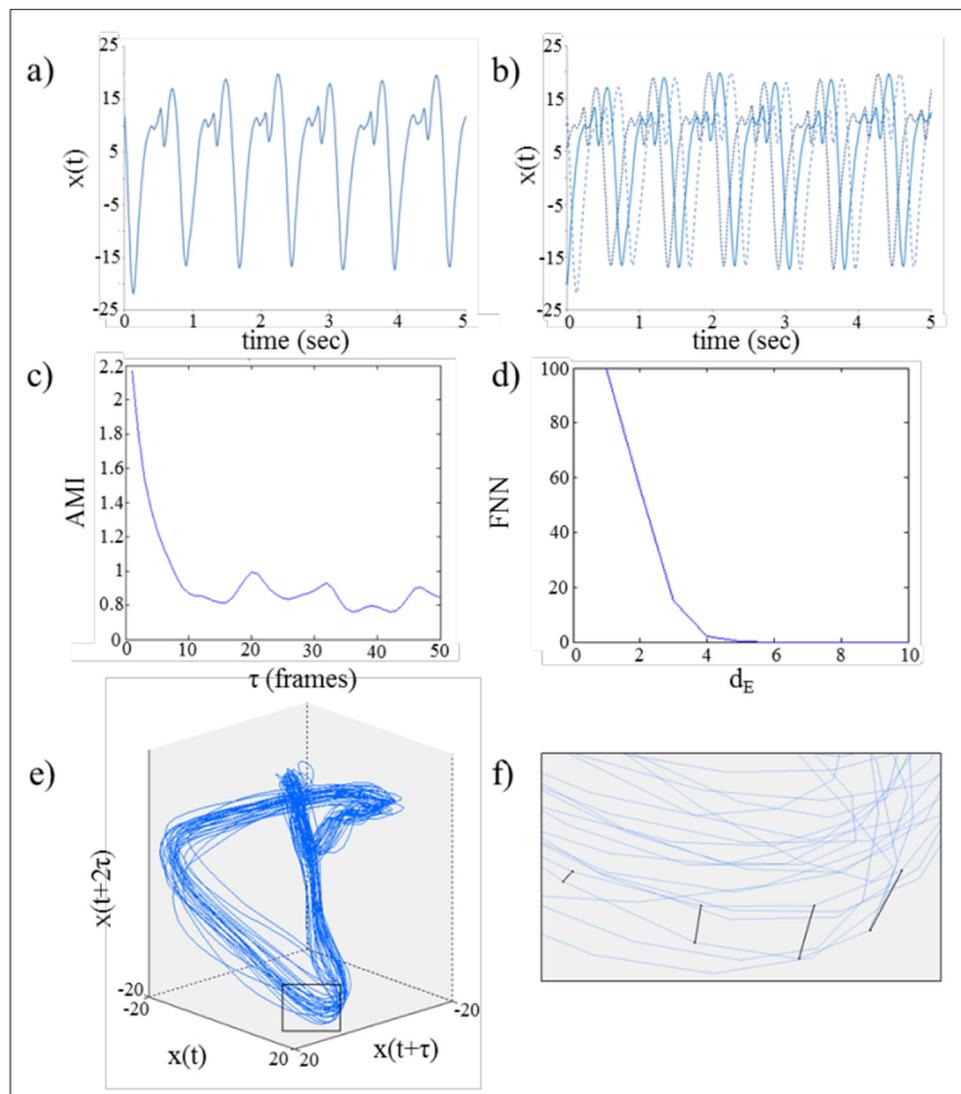
Fig. 2. Estimation of the largest Lyapunov exponent requires several steps. a) Original time series joint angles used. b) Time delayed copies of the original time series were created. The size of the time delay is dependent upon the results from (c) the average mutual information algorithm and (d) the false nearest neighbors algorithm. e) When each time delayed copy is plotted against each other in state space (3 dimensions in this example), the rate of divergence between nearest neighbors can be calculated. f) An inset from the rectangle in (e) depicting nearby neighbors in state space.

3 data points and was divided by the sampling rate to obtain a measure of time [19].

Additionally, the Wolf algorithm requires several input parameters including, the number of steps (k = 3), the maximum angle (0.3 radians), the minimum scale length (0.0001) and the maximum scale length (0.1) for finding a replacement nearest neighbour [20]. The values for the input parameters were based upon previous work with kinematic data [19,21]. The same number of strides were used for all analyses across all participants. The trial with the minimum number of strides was used and all other shoe condition trials were truncated to have the same number of strides by removing data from the end of the trial (216 strides used).

For each running trial, the reconstruction lag and embedding dimension were calculated. As the embedding dimension did not differ greatly from trial to trial it was set to 7 for the ankle, 6 for the knee and 6 for the hip. Individual reconstruction lag was used for each trial.

2.7. Statistics

A three way mixed general linear model was used for statistical analysis. Independent variables included within subject factors of

midsole stiffness and midsole thickness and a between subject factor of group (novice or trained). For any significant interactions, paired t-tests were conducted to determine where the difference was significant. Significance was set to p = 0.05 prior to conducting the study. Heart rate data were averaged over the running trial. Independent two tailed t-tests were used to compare average heart rate between groups for each shoe to ensure heart rate values were similar between Trained and Novice Runners.

3. Results

Participants in the trained running group ran 61.7 km/week on average. The novice running group confirmed that they ran less than a total of 10 km in the past year. Demographic results can be found on Table 1. Running speed determined from the warm up trial, was 11.2 (1.35) km/hr for the trained running group and 8.5 (0.8) km/hr for the novice running group. Average heart rate values ranged from 140 bpm to 146 bpm and were not significantly different (p > 0.41) between groups for all shoe conditions.

Table 1
Average(SD) participant demographics.

	Novice	Trained
Age (Y)	21.5 (2.71)	23.3 (5.82)
Height (m)	1.77 (0.06)	1.75 (0.05)
Weight (Kg)	75.8 (9.8)	68.3 (5.1)
Weekly Mileage (km/week)		61.7 (28.2)
Easy Training Pace (min/km)		4:37 (0:23)
Hard Training Pace (min/km)		3:36 (0:20)

Table 2
Average reconstruction lag (τ) for each shoe condition and joint for the two training level groups.

	Shoe 1	Shoe 2	Shoe 3	Shoe 4
Ankle				
Novice	14.3 (1.7)	14.0 (1.8)	14.0 (2.3)	13.9 (2.2)
Trained	10.6 (1.9)	10.5 (2.1)	12.5 (3.0)	10.3 (3.1)
Knee				
Novice	10.1 (0.9)	10.2 (0.9)	10.2 (0.9)	10.2 (0.9)
Trained	8.5 (1.73)	8.4 (1.67)	8.5 (1.8)	8.4 (1.7)
Hip				
Novice	19.6 (3.0)	19.3 (2.9)	19.0 (2.5)	19.0 (2.5)
Trained	14.8 (3.7)	14.8 (3.7)	15.0 (3.8)	14.9 (3.8)

3.1. Input parameters

The reconstruction lag found for each joint and shoe condition are presented in Table 2.

3.2. Ankle LyE

A main effect of group was observed for the LyE for the ankle joint (F 121 = 13.64, p = 0.001). Novice runners had significantly larger LyE values compared to trained runners indicating less stability compared to trained runners (Fig. 3a). There were no significant interactions or main effects for midsole thickness or stiffness for the ankle LyE.

3.3. Knee LyE

The LyE for the knee was greater in novice runners compared to trained runners (F 121 = 31.61, p < 0.001) indicating lower stability compared to trained runners. Similar to the ankle, there were no differences in LyE for the knee across shoe conditions.

3.4. Hip LyE

The LyE for the hip had a significant interaction between running group and midsole thickness (F 121 = 4.79, p = 0.04). *Post hoc* analysis revealed that the novice running group had larger LyE values at the hip in traditional shoes compared to minimal shoes (t (9) = 2.60, p = 0.029) indicating less stability at the hip in shoes constructed with thicker midsoles. In the trained running group, there were no differences between shoes with differing midsole thickness. The trained running group had significantly lower LyE values for the hip across all shoe conditions (F 121 = 21.83, p < 0.001). Results from all three joints can be found in.

4. Discussion

It was originally hypothesized that novice runners would be have less stability compared to trained runners. The results from the LyE values at the ankle, knee and hip support this notion as trained runners displayed increased stability across all shoe conditions tested. The second hypothesis of this study aimed to influence local dynamic
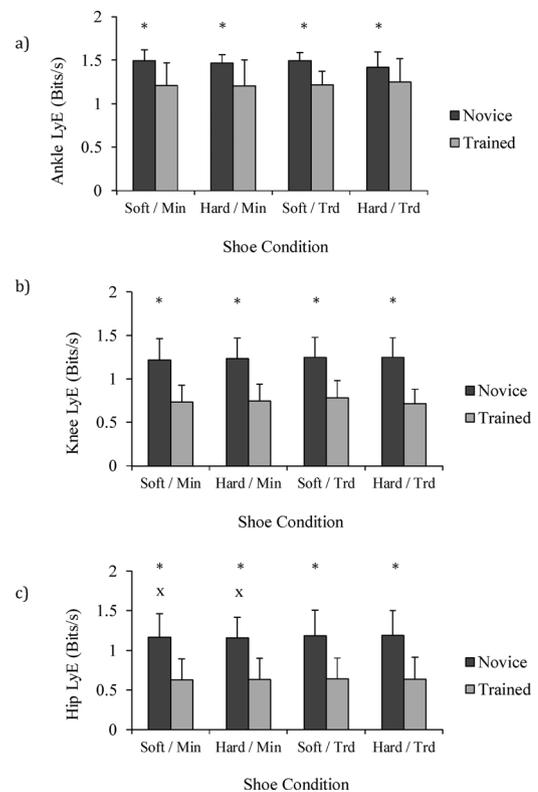
Fig. 3. Mean values (error bars indicates 1 S.D.) for the LyE for the ankle (a), knee (b) and hip (c). Group differences are denoted by *. Across all three joints, trained runners displayed decreased attractor divergence. The letter 'x' denotes a group x thickness interaction.

stability by manipulating midsole characteristics. It was found, in both groups, that increasing both midsole stiffness and thickness did not have an effect on local dynamic stability. The only significant interaction that existed was for the novice running group's divergence at the hip while running in traditional shoes compared to minimal shoes. In traditional shoes, there was decreased stability compared to the thin, minimal shoes indicating novice runners had less stability at the hip while wearing footwear with thicker midsoles.

4.1. Group comparisons

Trained runners displayed increased stability at the ankle, knee and hip across all shoe conditions. This finding compliments previous work using detrended fluctuation analysis (DFA) to compare long term correlations in novice and trained runners [3]. DFA uses multiple discrete data inputs such as stride interval time which gives an indication of how the system varies its cycle time. The current findings show how stability is different at an individual joint level, which may contribute to the overall timing of the stride interval variability from Nakayama et al. (2010). With repeated exposure, it is assumed that the body naturally refines motor output consistency, which was seen in the trained runners compared to the novice runners. The results presented lead to further questions regarding the end points for overly stable and unstable movement patterns. The point at which a movement pattern is injurious remains unknown. As this study shows a difference in dynamic stability between different levels of running experience it can be assumed that a novice runner with training may experience changes in control. The rate of change in dynamic stability with training remains unknown.

4.2. Shoe comparisons

Running stability at the ankle, knee and hip were the same across all shoe conditions. The degree to which midsole stiffness and thickness were manipulated, was not great enough to have an effect on local dynamic stability. The midsole stiffness's included were specifically extreme with respect to typical material used in commercially available running footwear (50–55 Asker C), representing extremely hard and extremely soft midsoles. This means that altering midsole stiffness within the bounds of the range of commercially available footwear will not affect local dynamic stability. The innate pattern of running for all participants, regardless of experience was unaffected by the perception of different midsoles. Current findings highlight that it is not the shoes one is wearing but rather the amount of running experience that is related to the amount of stability in the lower limbs. Postural control research has found improved stability in single legged balance while barefoot [8]. Other work has found increased variability while running barefoot compared to shod conditions [22]. It has been hypothesized that running barefoot results in greater variability due to an impact avoidance strategy, however this remains unproven [23].

The goal of the minimal shoes in this study was to decrease the amount of movement stability by increasing the perception of impact, as seen in barefoot research. However, the conditions that were used did not alter stability implying that the minimal condition was not severe enough to cause a change. Barefoot conditions allow direct information from the ground to the foot [23]. In both the minimal and traditional shoe conditions tested, the foot was on top of an insole, which was on top of different midsoles, which is quite different than being barefoot. It is important to note that afferent information from the dorsum of the foot while shod may also play an important role in the control of running variability. Recent work has compared the transition to barefoot running and found increased instability [24]. It remains unknown if the changes are due to differences in cushioning underfoot or lack of experience while barefoot running. Isolating feedback from the plantar or dorsal surface of the foot while running may also be beneficial in understanding if the upper of a shoe aids in reduced variability while shod.

4.3. Limitations

Several limitations in the current study should be noted. First, it has been shown that local dynamic stability is different between over ground and treadmill walking [25]. LyE is reduced while walking on a treadmill compared to over ground. It is unknown whether running or running experience alters attractor divergence between treadmill and over ground testing. It is also known that the treadmill surface has compliance. A compliant surface may mask the differences in cushioning properties between shoe conditions. For this reason, the middle of the treadmill bed was reinforced to reduce the effect of bed compliance. Matching the intensity of running between groups of different fitness levels was a challenge. It was assumed that absolute heart rate would give the best indication of the effort for an individual. It is assumed that a trained runner would have a lower resting heart rate, and at ~150 bpm, would be running at a preferred speed that was greater than a novice runner. It is assumed that both groups were running at the same preferred pace relative to their given running experience.

4.4. Conclusions

The results from the current study examined the effects of running experience and midsole properties on local dynamic stability. Increased running experience was strongly associated with increased local dynamic stability at the ankle, knee and hip in the sagittal plane. It was also found that midsole material does not have an effect on local dynamic stability. There was an interaction at the hip as novice runners displayed increased attractor divergence in thick soft shoes. This is

important, as it will take more than a change in midsole geometry and material stiffness to influence one's movement stability. It appears as though it is their experience in conducting the movement that has greater impact on the amount of local dynamic stability. It remains unknown if shoes with atypical construction such as rocker shoes or unstable shoes would have an effect on local dynamic stability. The rate of change in local dynamic stability is still unknown in novice runners as they transition into trained runners. Current findings may help classify those who can be considered novice or trained runners. Future work should aim to further understand how shoe construction could affect local dynamic stability for the benefit of athletic performance or injury prevention.

Conflict of interest

The authors declare no conflict of interest.

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