ASYMMETRY CHANGES DURING DISTANCE RUNNING IN RECREATIONAL RUNNERS

by

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Bilateral asymmetry is a difference in shape, size, and form on two sides of a given axis (Maloney et al., 2019). As fatigue increases during running, there is greater metabolic energy cost and lower mechanical efficiency (Mizrahi et al., 2000) which may be associated with increased asymmetry. This study aimed to determine asymmetry changes between right and left foot peak accelerations and at the sacrum during an outdoor run. Twenty-four runs from 8 participants (5F/3M) training for either a half marathon or a marathon were analyzed. Participants wore inertial measurement units and ran self-selected routes (13.7±4.5 mi) and pace (9:24±1:10 min/mi). Asymmetry was calculated using symmetry angle expressed as a percentage, where 0% is perfect symmetry (Zifchock et al., 2008). Runs were grouped into lower mileage (<13.5 mi) or higher mileage (>13.5 mi) groups and symmetry angle was averaged over quarters of each run. Significance was tested for using a one-way ANOVA. Symmetry angle was not significantly different over quarters of lower mileage group or higher mileage group runs or between groups. However, there was a trend in all runs of average symmetry angle increasing at the feet during each quarter. Additionally, average symmetry angle tended to be larger in the higher mileage group compared to the lower mileage group. Samples showed great variance in symmetry angle size indicating that individual participants may have significant changes in

asymmetry. Understanding running mechanics in the natural running environment can provide useful insight into running technique and injury prevention.

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Introduction

Running is a popular form of exercise that millions of people around the world engage in. The vast majority of running studies were completed indoors, and while this does provide important insight, indoor and outdoor running gaits differ (Lafferty et al., 2021). Additionally, most indoor running studies only examined running over short distances (Benson et al., 2022). Inertial measurement units (IMUs) are small wearable sensors capable of measuring running mechanics through changes in linear and angular position outside of the laboratory during free runs in the natural environment. Understanding changes in running mechanics throughout the duration of runs in the natural environment can help provide useful insight into running technique and injury prevention. One particular area of running mechanics that can be examined using IMUs during outdoor running is asymmetry between the peak acceleration of the lower limbs. Asymmetry changes can tell us about how the runner's form and efficiency changes throughout the run. Therefore, the purpose of this study is to determine how asymmetry changes between the right and left foot peak accelerations, as well as the sacrum, throughout an outdoor run greater than seven miles.

Symmetry

Symmetry in athletics is when there is exactly the same shape, size, and form on both sides of a given axis, whereas bilateral asymmetry indicates a difference between the two sides of an axis (Maloney, 2019). One way asymmetry can arise is through lateral limb preference. Lateral preference is the tendency to use one side over the other when completing voluntary motor acts (Carpes et al., 2010). For example, favoring the right foot when kicking a ball or stepping forward with the right foot to initiate walking. Throughout walking and running, there is a natural level of asymmetry. Asymmetry less than 10% while running is considered a normal level of asymmetry (Stiffler-Joachim, 2021a).

What affects asymmetry

Bilateral asymmetry is affected by running speed as well as running experience (Mo et al., 2020). In competitive runners, asymmetry decreased as the speed increased, however in recreational runners there was a U-shaped trend in asymmetry where gait was most symmetrical around preferred speed (Mo et al., 2020). Furthermore, in novice runners, there were no consistent changes in asymmetry bilaterally (Mo et al., 2020). Therefore, the impact of speed on asymmetry is dependent on the individual's level of running experience.

In addition to speed and experience, fatigue has been found to contribute to asymmetry levels. As fatigue increases, the running mechanics change resulting in a greater metabolic cost (Mizrahi et al., 2000). Greater metabolic cost can be associated with lower mechanical efficiency. Symmetry between limbs is suggested to contribute to greater mechanical efficiency (Melo et al., 2020). In a study of runners completing a 10k, the mechanical efficiency decreased and the symmetry index between the right and left sides also decreased as the run progressed (Melo et al., 2020). Furthermore, as fatigue increases, there is also an increase in the vertical acceleration of the lower leg (Mizrahi et al., 2000). Changes in vertical acceleration while running can be a model of impact loading in the limbs, suggesting there is increased loading in the limbs as fatigue increases.

An indoor study by Radzak et al. used a speed blinded exhaustive protocol to induce fatigue in a group of runners and found some variables became less asymmetric and others became more asymmetric (Radzak et al., 2017). In the fatigued state, the vertical stiffness and loading rate between limbs became less asymmetric (Radzak et al., 2017). The study predicted this to be caused by an increase in stiffness in the initially less stiff limb creating more symmetrical stiffness between the limbs (Radzak et al., 2017). However, asymmetry between the limbs increased in knee internal rotation and knee stiffness during the fatigued state (Radzak et al., 2017). This suggests that while symmetry increases in the overall neuromuscular stiffness in the fatigued state, knee stiffness is becoming more asymmetrical (Radzak et al., 2017). This could mean that the knee is compensating for other changes in the lower leg as a result of fatigue and this causes only parts of the legs to become more asymmetric with fatigue.

How asymmetry is calculated

Asymmetry between limbs can be calculated using many different indices. One of the most common measures of asymmetry is the symmetry index (Zifchock et al., 2008 and Cabral et al., 2016). The symmetry index is calculated using the equation:

$$symmetry\ index = \frac{X_{Right} - X_{Left}}{\frac{1}{2}(X_{Right} + X_{Left})} \times 100 \text{ (Cabral et al., 2016)}$$

where X_{Right} is a metric from the right and X_{Left} is a metric from the left side to give a percentage of symmetry between the two sides. One limitation of this method is that it requires the use of a reference value, as seen as the denominator of the above equation, which can cause artificial inflation of the differences between the two sides (Cabral et al., 2016). Another way to calculate asymmetry is using the symmetry angle. The symmetry angle is calculated using the equation:

$$symmetry\ angle = \frac{45° - arcTan(X_{Left}/X_{Right})}{90°} \times 100$$

and compares the relationship between the discrete values of the left and right sides to a line of symmetry (Zifchock et al., 2008).

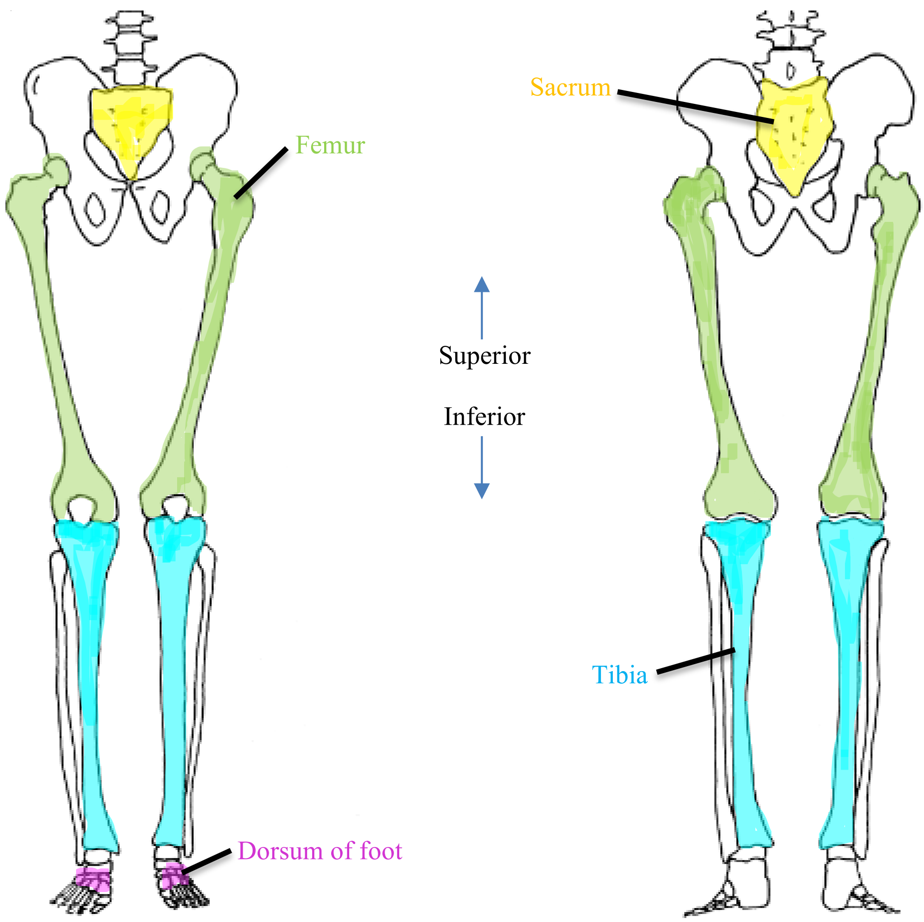
Ways to measure asymmetry

There are a variety of devices and tools used to measure asymmetry while running inside the laboratory, including 2-D or 3-D motion capture systems, where reflective markers are placed on the body of interest and recorded using cameras that surround the capture space (Radzak et al., 2017., Cabral et al., 2016., and Arampatzis et al., 1999). Force plates are another way to measure differences between impact loading between the two legs (Arampatzis et al., 1999) and electromyography can measure muscle activation differences (Mizrahi et al., 2000). In recent years, developments in technology have advanced the use of IMUs allowing researchers to measure peak acceleration between sides in the outdoors (Lee et al., 2010 and Benson et al., 2022).

Inertial measurement units

Peak tibial accelerations have been shown to be correlated to the peak vertical loading rate (Van den Berghe et al., 2019). As a result, peak accelerations detected by IMUs can be used to predict impact loading while running (Tan et al., 2021). Peak vertical acceleration has been found to be greater in one limb of runners compared to the other (Napier et al., 2022). Peak acceleration as a representation of impact loading suggests that there is asymmetry between the impact loading of each limb.

The tibia and foot have been reported as optimal placements for IMU sensors to provide accurate impact loading assessments when running (Tan et al., 2021) (Figure 1). However, peak tibial acceleration occurs after the impact is attenuated by the ankle joint, resulting in lower peak accelerations than experienced at the foot (Cheung et al., 2018). Lower placement of the IMU along the lower limb results in more accurate representations of the foot and ankle accelerations (Sheerin et al., 2019). Additionally, a study validated the use of a single IMU to measure vertical center of mass (COM) acceleration in comparison to an infrared camera system (Lee et al., 2010). Furthermore, the single IMU was shown to be able to detect varying levels of asymmetry in the COM following a left and right foot strike (Lee et al., 2010).



Modified from Society of Asylum Medicine

Figure 1: Common anatomical locations for lower limb placement of IMUs.

Outside vs inside running

Running gait can be measured in real-world environments through the use of IMUs (Napier et al., 2017). Most studies using IMUs have looked at running in controlled environments such as indoors and over short distances (typically less than 200 m) and at assigned speeds (Benson et al., 2022). While it is helpful to control and eliminate other factors in order to isolate the examined outcome when conducting biomechanical research, running completed in the lab might not be fully reflective of how runners actually run in the real world. Indoor running gait may not adequately reflect gait seen in natural running environments, with the only moderate similarities in foot strike at initial contact and rearfoot position at midstance (Lafferty et al. 2021). This can create problems when adjustments to running or treatment of an injury are based solely on data collected in an indoor and controlled lab setting (Lafferty et al., 2021).

Asymmetry and injury

Asymmetry may influence running performance and running-related injuries. Restoration of symmetry is often the goal of clinical treatment plans in addition to preventing recurring or new injuries (Zifchock et al., 2006). As a result, it is important to understand what impacts asymmetry and when asymmetry is considered normal. Increases in hip adduction angle, as well as knee internal rotation and velocity, are related to knee overuse injury (Radzak et al., 2016). Additionally, previously injured limbs experience greater loading than the uninjured limb, and high peak shock values increase risk for tibial stress fractures (Zifchock et al., 2006). Asymmetry may influence which side of a runner may become injured (Zifchock et al., 2006). Increased asymmetry is correlated with greater energy expenditure and lower efficiency (Stiffler-Joachim et al., 2021b). Understanding the asymmetry of impact loading at the level of the foot and at the sacrum can help with better understanding how injuries can arise, as well as aid in the development of techniques to minimize injury and improve performance.

Specific aims of this study

Many studies have examined how speed, experience level, and fatigue impact asymmetry in running inside the laboratory. However, little research has investigated how the body adjusts and adapts in response to long-distance runs. Therefore, this study aimed to determine how the asymmetry between lower limbs changes over long-distance training runs in recreational runners. We predict that as the run progresses, the asymmetry between the left and right foot and the sacrum following a right and left foot strike will increase.

Methods

Participants and runs

Institutional Review Board approval was obtained prior to data collection and all participants provided informed consent. A total of 24 training runs from 8 participants were analyzed (5 females, 3 males; 31.25 ± 6.39 years, 167.42 ± 6.22 cm, 62.32 ± 9.90 kg) (Table 1). All participants were recreational trained runners running a minimum of 10 miles a week and part of a training program for either a half marathon or full marathon. The data were collected during free training runs where the participant ran a self-selected route at a self-selected pace. All analyzed runs were a minimum of seven miles long with an average length of 13.7 ± 4.5 miles and an average pace of 9:24 ± 1:10min/mile.

Table 1: Demographics from the eight recreational runners that were a part of a training program for either a marathon or half marathon (5F/3M).

Age (years)	Weight (kg)	Height (cm)	Distance (miles)	Time (min/mile)
31.25 ± 6.39	62.32 ± 9.90	167.42 ± 6.22	13.7 ± 4.5	9:24 ± 1:10

Data collection

Three IMUs (Casio, Tokyo, JPN) were synced by creating an identifiable waveform prior to and following the main collection. Two IMUs were clipped into place bilaterally on the laces of the shoes and one was clipped onto the waistband of the pants at the level of the sacrum (Figure 2). IMUs recorded at 200 Hz. Participants were also equipped with a GPS watch to record pace, distance, and heart rate at 1 Hz (Garmin, Olathe, KS, USA).

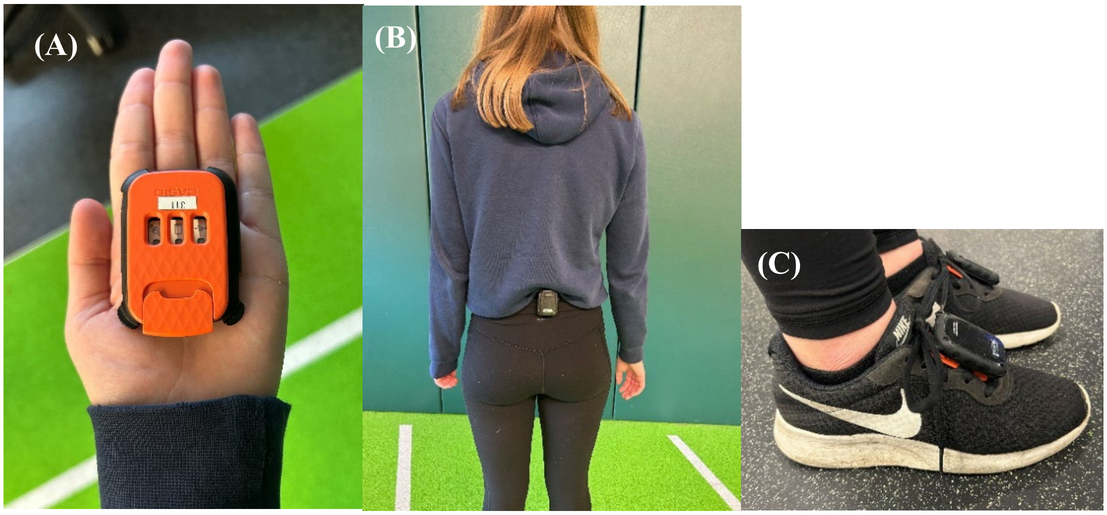


Figure 2: Inertial measurement units that each participant wore. Left image (A) shows a single inertial measurement unit (IMU). Center image (B) shows IMU placement on the waistband of the pants. Right image (C) shows the IMU placement on the shoes.

Processing

IMU data and GPS data were analyzed in custom Matlab scripts (Mathworks, Natick, MA). The accelerometer data from the IMUs were visualized to show the acceleration magnitudes over time. The waveform created from syncing the three IMUs together was used to align the time-based waveforms. The GPS data were plotted to show speed over time. The first point of running in the IMU data were synced with the first point of running speed from the GPS data to sync the IMU and GPS timelines. The GPS data were upsampled to have the same number of data points for the GPS and IMUs. IMU data were trimmed to where the running started and ended. The trimmed IMU data were then run through another custom Matlab script to find the peak acceleration in each left and right foot strike, as well as in the sacrum. The sacral data were separated by peak accelerations following a left or right foot strike. Sacral accelerations following right foot strikes were labeled as right sacrum and sacral accelerations following left foot strikes were labeled as left sacrum. The peak accelerations for the left foot, right foot, left sacrum, and right sacrum were plotted over time (Figure 3). Gaps in running were identified as periods with notably smaller peak accelerations or where the acceleration data did not match the pattern of the rest of the collection (Figure 4). Gaps were removed from the data set. Data during a single run were trimmed to match the variable (right foot, left foot, right sacrum, left sacrum) with the fewest data points in order to make comparison between the right and left side.

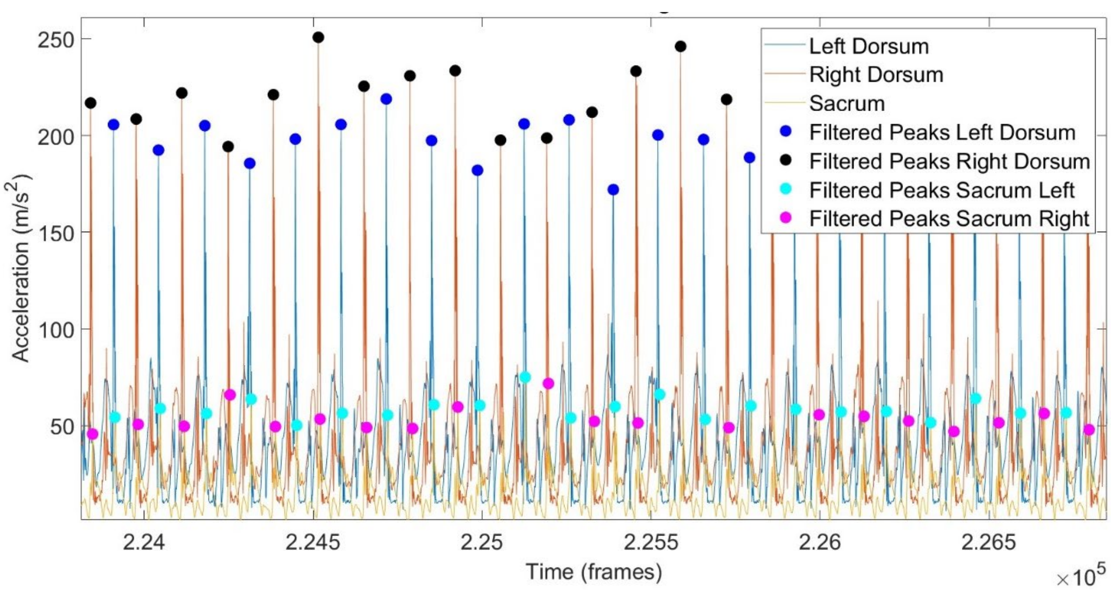


Figure 3: A sample of identified peak accelerations at the feet and sacrum during an outdoor long-distance training run.

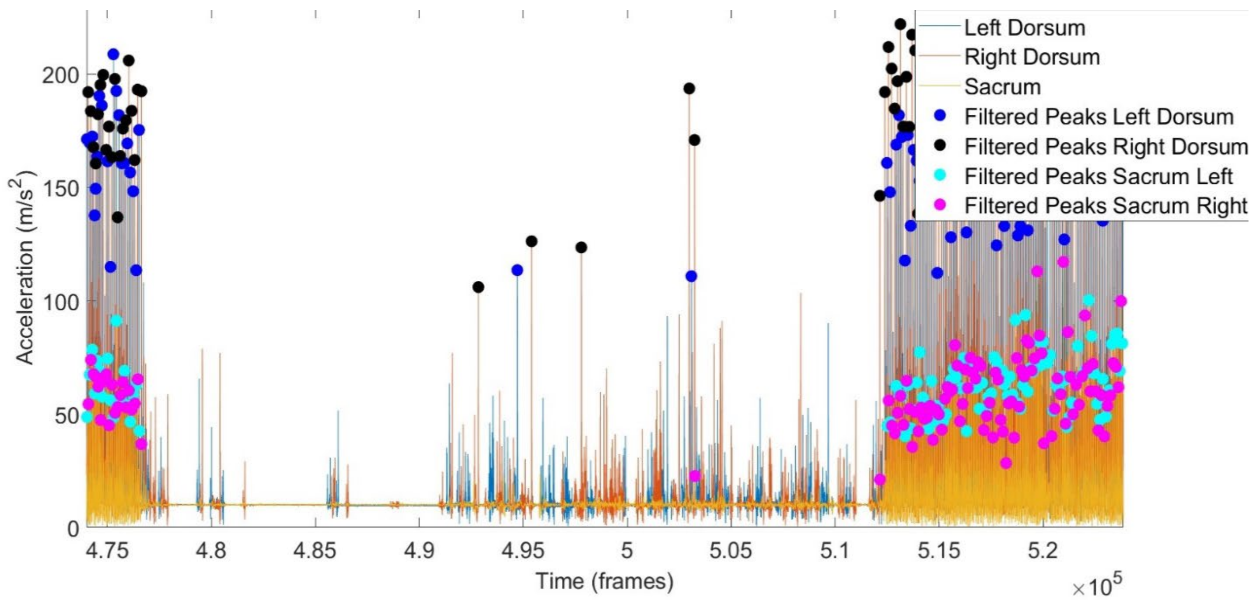


Figure 4: Example of gap in running data that were removed from the data set. Participant was not running during this time (i.e stop light, walking break, etc).

Analysis

Asymmetry was calculated using the symmetry angle:

$$symmetry\ angle = \frac{45° - arcTan(X_{Left}/X_{Right})}{90°} \times 100 \text{ (Zifchock et al., 2008)}$$

where X_{Left} was the peak acceleration on the left side and X_{Right} was the peak acceleration on the right side. The symmetry angle was chosen to remove the use of a reference leg, which can cause inflated results and limited comparisons between groups (Cabral et al., 2016). The symmetry angle is a measure of the angle created when plotting discrete values for the left and right sides, where 45 degrees is perfect symmetry (Zifchock et al., 2008). The angle is then converted to a percentage, where 0% is perfect symmetry and 100% is when the two sides are completely asymmetric in equal and opposite magnitudes (Zifchock et al., 2008). For this study, 0% means that the right and left sides have the exact same peak acceleration. Asymmetry was calculated between the right foot and the left foot and between the right sacrum and the left sacrum for a singular gait cycle resulting in separate symmetry angles for the feet and the sacrum. The symmetry angles were averaged over quarters of each run to capture the early, middle, late, and ending stages of the run. Runs were grouped into lower mileage (<13.5 miles) or higher mileage (>13.5 miles). Groups were formed to make comparable analyses between quarters in the same group and were based on the average distance of all the runs (13.7 miles). Additionally, percent change was calculated for both the lower mileage and higher mileage groups using the equation:

$$\%\Delta = \frac{(X_{n+1} - X_n)}{X_n} \times 100$$

where x_n represents the average symmetry angle for a given quarter of the run. Maximum percent change was also calculated using the above equation where X_{n+1} was the quarter with the greatest symmetry angle and X_n was the quarter with the smallest symmetry angle.

Stats analysis

Data were compared within the same milage group and between the two groups. A one-way repeated measures analysis (ANOVA) was used to compare symmetry angles among quarters of the run ($\alpha = 0.05$).

Results

Symmetry angles were not significantly different throughout the quarters of the lower or higher mileage run ($p>0.05$). The average symmetry angle for the sacrum in the lower mileage group was 5.50 ± 1.69% during the first quarter, 5.60 ± 1.85% during the second quarter, 5.29 ± 1.46% during the third quarter, and 5.75 ± 1.55% during the fourth quarter (Figure 5). The average symmetry angle in the feet was 5.18 ± 2.15% for the first quarter, during the second quarter was 5.27 ± 3.04%, during the third quarter was 5.33 ± 3.13%, and during the fourth quarter was 5.43 ± 3.32% (Figure 5).

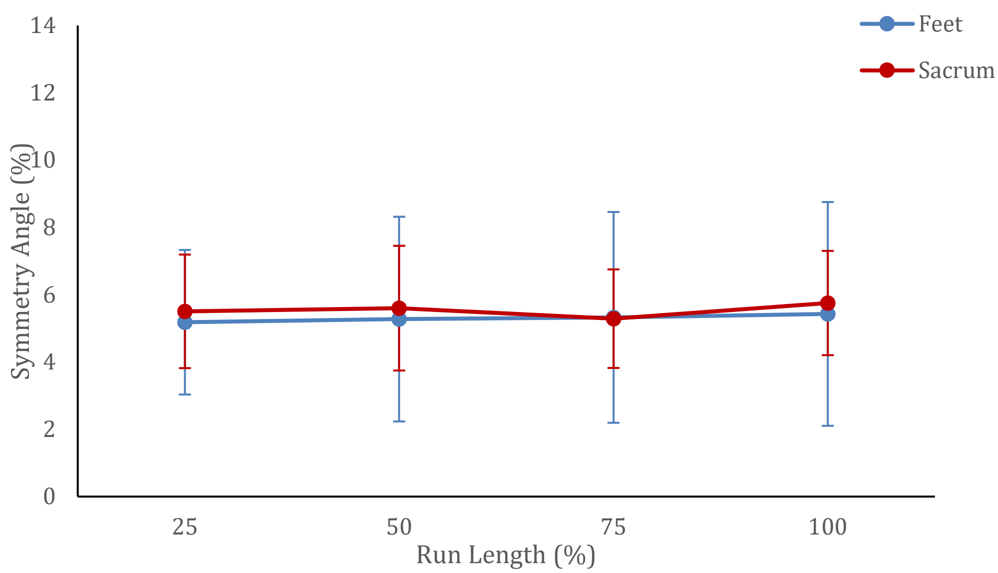


Figure 5: Average asymmetry percentage over each quarter of the run in the feet and sacrum for lower mileage runs (n = 13).

The average symmetry angle in the higher mileage group for the sacrum was 5.65 ± 2.84% during the first quarter, 5.16 ± 2.83% during the second quarter, 5.41 ± 2.47 % during the third quarter, and 5.24 ± 2.53% during the fourth quarter (Figure 6). For the feet, the average symmetry angle was 7.06 ± 3.16% during the first quarter, 7.19 ± 3.92% during the second quarter, 8.46 ± 4.26% during the third quarter, and 9.17 ± 4.68% during the fourth quarter (Figure 6).

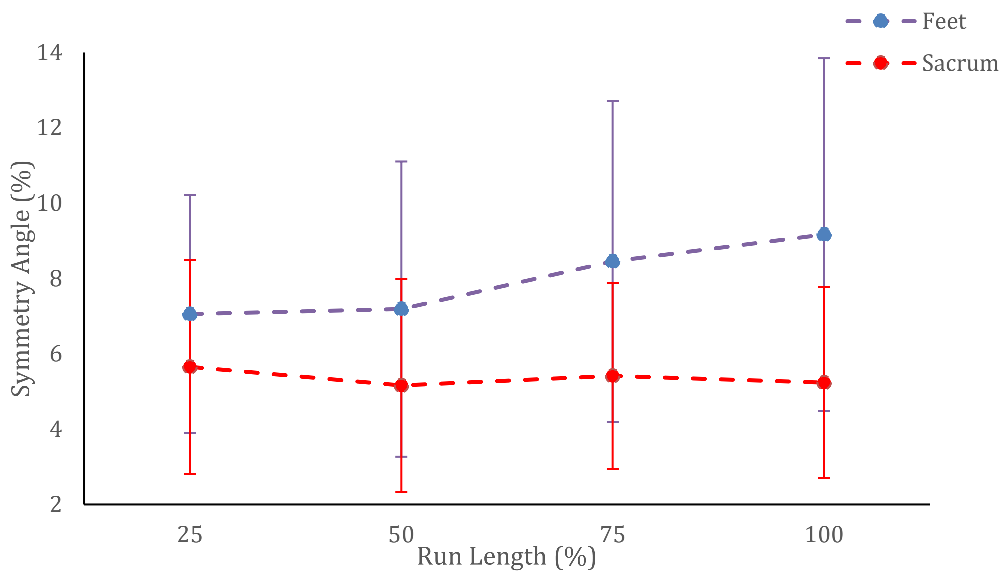


Figure 6: Average asymmetry percentage over each quarter of the run in the feet and sacrum for higher mileage runs (n = 11).

There was not a significant difference in the symmetry angles between the lower and higher mileage groups in either the symmetry angles of the feet or sacrum ($p>0.05$). The changes in the average symmetry angle were greater in the higher mileage group compared to the lower mileage group (Figure 7). The maximum percent change in the average symmetry angle of the feet across all quarters was 4.76% in the lower mileage group and 29.92% in the higher mileage group (Table 2). The maximum percentage change in the average symmetry angle of the sacrum between all quarters of the run was 8.79% in the lower mileage group and 9.55% in the higher mileage group (Table 2). In the lower mileage group, the percent change was greatest between quarters 3 and 4 for both the feet and sacrum with a change of 1.92% in the feet and 8.79% in the sacrum (Table 3). In the higher mileage group, the percent change was greatest between quarters 2 and 3 for the feet with a change of 17.65%, and between quarter 1 and 2 for the sacrum with a change of -8.71%Δ (Table 4).

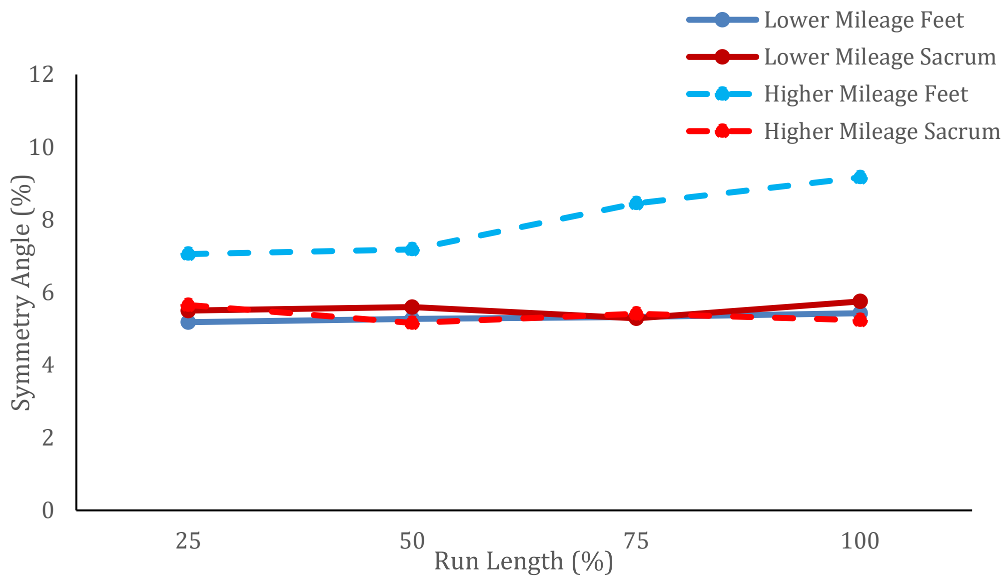


Figure 7: Average asymmetry percentage over each quarter of the run in the feet and sacrum for all runs (n = 24).

Table 2: Overall maximum percent change among the quarter of the run for the lower mileage group and higher mileage group.

Symmetry angle location	Lower Mileage Group (%Δ)	Higher Mileage Group (%Δ)
Feet	4.76	29.92
Sacrum	8.79	9.55

Table 3: Percent change between each quarter of the run for the lower mileage group. Negative values represent decreases between quarters.

Symmetry angle location	Quarter 1 to 2 (%Δ)	Quarter 2 to 3 (%Δ)	Quarter 3 to 4 (%Δ)
Feet	1.81	0.96	1.92
Sacrum	1.72	-5.57	8.79

Table 4: Percent change between each quarter of the run for the higher mileage group. Negative values represent decreases between quarters.

Symmetry angle location	Quarter 1 to 2 (%Δ)	Quarter 2 to 3 (%Δ)	Quarter 3 to 4 (%Δ)
Feet	1.86	17.65	8.41
Sacrum	-8.71	4.82	-3.16

There was poor correlation between the feet and the sacrum for both the lower mileage runs (R^2 = 0.42) and higher mileage runs (R^2 = 0.38) (Figure 8).

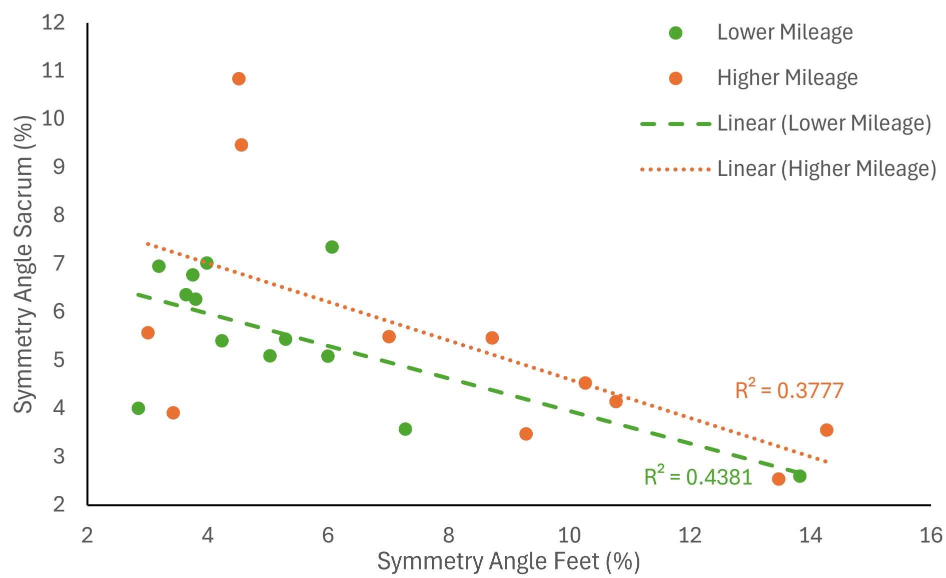


Figure 8: Correlation between the average asymmetry in the feet and sacrum for the lower mileage group and higher mileage group.

Discussion

The purpose of this study was to determine how training run distance impacts asymmetry changes between lower limbs. There was no statistically significant difference between quarters of the run for the lower mileage group or the higher mileage group. While not statistically significant, the symmetry angle at the feet tended to increase from quarter to quarter for both the higher mileage group and lower mileage group. There was no clear pattern in the sacrum for either the lower mileage group or the higher mileage group. The consistent increase in symmetry angle in the feet suggests that the feet are become slightly more asymmetrical as the run goes on. However, the inconsistency at the sacral level suggests that there are less changes over time in the amount of asymmetry the sacrum experiences following a left foot strike compared to a right foot strike. Additionally, the poor correlation between the feet and the sacrum for both the lower mileage group and the higher mileage group suggests that the asymmetry in the feet is not dependent on the asymmetry in the sacrum. Nor is the asymmetry in the sacrum is dependent on the asymmetry in the feet.

There was also no statistically significant difference between the overall higher and lower mileage runs. However, it is interesting to note that there was a greater magnitude of change between the quarters in the higher mileage group than the lower mileage group. This suggests that throughout a higher mileage run there may be greater changes in asymmetry than in a lower mileage run.

It is also interesting to note that the difference in the percent change was much greater in the feet between the lower and higher mileage groups compared to the sacrum. In the feet, the difference in percent change was 20.37% and the difference in the sacrum was 4.03%. This suggests that asymmetry changes tend to be greater at the feet than at the sacrum. This could mean that as the force travels upward, the body tries to equalize it on both sides and limit the amount of asymmetry the body experiences superior to the feet.

In a study by Radzak et al., they found that when fatigue was induced in runners, there was increased asymmetry in knee internal rotation and knee stiffness (Radzak et al., 2017). However, there was less asymmetry in overall limb stiffness (Radzak et al., 2017). Their study suggested that the asymmetry increase in the knee helped maintain more symmetrical neuromuscular stiffness as the runners became more fatigued (Radzak et al., 2017). Our current study only looked at asymmetry at the feet and at the sacrum. It is possible that there is increased asymmetry in the knee as the run progresses and that the knee compensates for the rest of the leg and maintains the asymmetry level in the feet and the sacrum.

All runners have some level of asymmetry when running. When the asymmetry is less than 10%, it is considered normal (Stiffler-Joachim, 2021a). In the current study, only one participant had asymmetry values that were consistently above 10% at the feet. However, changes between quarters of the run were not statistically significant for all the runs. This could mean that the body adjusts the running form to minimize increases in asymmetry and avoid potential injury.

A study by Mo et al. found that running experience impacts the amount of asymmetry a runner experiences at different speeds (Mo et al., 2020). For recreational runners, their gait was most symmetrical around their preferred speed, and they ran more asymmetrical when below and above that preferred speed (Mo et al., 2020). Runners in this study were able to choose their own pace during the analyzed runs and so it is possible that runners were staying within their preferred speed throughout the duration of the run. This could have resulted in similar levels of asymmetry throughout the run. It would be interesting for future studies to examine if asymmetry levels changed differently based on amount of running experience or if asymmetry levels were different and different paces throughout a run.

There were several limitations to this study. One of which was that not all individuals had the same running form. In some individuals, the symmetry angle was greater in the sacrum than in the feet for their entire run. In others, it was the opposite. There were even some runners where the symmetry angle was greater in the feet for part of their run, but then it switched to being greater in the sacrum or vice versa. No two people run the exact same way, however grouping runs based on running form rather than mileage could lead to new insights into how the asymmetry changes during the run. Additionally, it could be that asymmetry is so individualized that trends cannot be seen across a group of people, but trends could be seen in an individual's running over time. There were a few subjects that did have substantial difference between the quarters of their run during the higher mileage run. However, there were too few runs to compare to each other for each participant. A case study looking into a collection runs by one individual may be able to better show trends in asymmetry throughout the run. Furthermore, not all runners could have experience the same level of fatigue as their run progressed and some could have been more used to higher mileages than others. While fatigue can be difficult to measure, it may be worth comparing how asymmetry changes for runners with similar levels of training and at that rank their run at similar Borg rating of perceived exertion levels. Finally, our study only looked at asymmetry changes at the foot and the sacrum and did not take into consideration changes in the knee. Future studies could investigate how asymmetry changes in the knee throughout the outdoor run.

Understanding how asymmetry changes during running can be used to help runners form better gait patterns and be more efficient during running. Visual feedback of the vertical impact can allow participants to retrain their gait and reduce the occurrence of running-related injuries (Chan et al., 2018). After two weeks, participants had retrained their gait to have decreased vertical impact and significantly decreased the risk of running-related injuries one year later (Chan et al., 2018). Using similar principles of visual feedback, it could be thought that providing feedback on how asymmetrical the individual is running could lead to beneficial gait re-training and injury prevention. As technology advances, it could be interesting to see if this could be incorporated into a running watch so the runner could get real-time feedback as their run progresses.

Conclusion

Understanding how asymmetry changes throughout longer runs in the natural running environment is important to improve running form and prevent injuries. Many existing studies focused on indoor, controlled running over short distances and at fixed paces (Benson et al., 2022). Our study sought to determine how asymmetry changed during long free runs at a self-selected pace for recreational runners. We did this by having runners that were training for a marathon or half marathon wear IMUs while completing training runs.

While there were notable changes throughout the progression of a run, they were not statistically significant. One notable change was that the symmetry angle in the feet increased from quarter to quarter for both higher mileage runs and lower mileage runs. However, changes in the sacrum were inconsistent. This suggests that the amount of asymmetry may increase at the level of the feet but not at the level of the sacrum as the run progresses. Additionally, higher mileage runs had greater magnitude of change from quarter to quarter suggesting that the longer the run is, the more asymmetry the runner experiences as the run continues to progress.

Further research looking at how fatigued the runner is during each part of the run may give interesting insight into how asymmetry changes in response to fatigue during longer runs. Additionally, the symmetry angle varied greatly between participants and future studies could explore within-runner changes throughout the duration of a run. Another area of interest could be investigating asymmetry changes between runners with similar form and runners with similar levels of experience and training. Asymmetry is an important part of mechanical efficiency and having a better understanding of how it changes in the outdoor running environment can help runners develop better form and help clinicians develop more effective treatment plans.

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