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A Comparison of Running Shoe Optimal Stiffness and Speed

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ABSTRACT

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Purpose: Increasing the longitudinal bending stiffness of a running shoe decreases metabolic energy cost. Optimal stiffness occurs at the stiffness with the lowest metabolic cost. However, it is still unclear how optimal stiffness varies among individuals. The primary purpose of this study was to understand how optimal shoe stiffness is affected by running speed. A secondary purpose examined the anatomical and biomechanical characteristics associated with optimal stiffness variation. Methods: Six shoe stiffness conditions were manufactured by inserting carbon fiber plates between the midsole and outsole of a standard running shoe (shoe stiffness range: 9.26–23.83 N/mm). Twenty-one experienced male runners (mass = 67.1 ± 5.0 kg, height = 178.9cm ± 4.0 cm, age = 26.4 ± 8.4 years, American shoe size 10–11.5) completed testing at a slow 2.98 m/s and fast 4.47 m/s speed over two testing days, completing 5 min in each shoe condition. Metabolic cost was measured along with several biomechanical and anatomical variables. Data were also separated by foot strike to allow additional analysis. Results: At the fast speed, average optimal stiffness was 19.29 N/mm (± 5.62) with a metabolic benefit of 3.02% (± 2.62%). Slow speed average optimal stiffness was 17.04 N/mm (± 6.09) with a metabolic benefit of 1.93% (± 1.82%). Only rearfoot strikers demonstrated a significant increase in optimal stiffness ($p = .020$) and the associated metabolic benefit ($p = .024$) across speeds. There were no correlations between any of the measured anatomical or biomechanical variables and optimal stiffness. Conclusion: Optimal stiffness varied between subjects but was not correlated to any of our measured characteristics. Rearfoot striking runners may benefit from a high stiffness shoe at faster speeds to enable optimal performance.

Keywords: marathon racing, footwear, performance

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

Running economy is one of the most influential factors when examining a distance runner's performance and can be defined as the relationship between the velocity of running and the metabolic energy cost (measured in $\dot{V}O_2$ at a given running speed) (Daniels & Daniels, 1992). It is affected by a number of running shoe characteristics such as longitudinal bending stiffness, shoe mass, comfort, and cushioning (Fuller, Bellenger, Thewlis, Tsiros, & Buckley, 2015; Hoogkamer et al., 2017; Luo, Stergiou, Worobets, Nigg, & Stefanyshyn, 2009; Roy & Stefanyshyn, 2006).

Longitudinal bending stiffness (LBS) refers to the ability of a shoe to bend, limiting flexion and hyperextension of the forefoot joints. High LBS is associated with a lower running metabolic energy cost (Fuller et al., 2015; Hoogkamer et al., 2017; Madden, Sakaguchi, Tomaras, Wannop, & Stefanyshyn, 2016; Oh & Park, 2017; Roy & Stefanyshyn, 2006; Willwacher, König, Braunstein, Goldmann, & Brüggemann, 2014; Willwacher, König, Potthast, & Brüggemann, 2013). This metabolic cost reduction may be due to an anterior shift in the ground reaction force (GRF) point of application during stance (D. Stefanyshyn & Fusco, 2004; Willwacher et al., 2014, 2013). This anterior shift will lower metabolic cost by causing a slower plantar flexor shortening velocity and increased ground time (Di Michele & Merni, 2014; Fletcher, Groves, Pfister, & Macintosh, 2013). High LBS may also decrease negative and increase positive metatarsophalangeal (MTP) work (Madden et al., 2016; D. J. Stefanyshyn & Nigg, 2000; Willwacher et al., 2013). This may decrease the amount of possible energy loss that occurs at the MTP joint during gait.

Past studies show that metabolic cost decreases with increased LBS, but the benefits do not continue indefinitely, suggesting an optimal LBS specific to each runner (Oh & Park, 2017;

Roy & Stefanyshyn, 2006). Oh and Park found that subjects demonstrated an average decreased metabolic cost of 1.1–1.2% at optimal stiffness (2017). There is high variation in optimal stiffness along with the magnitude of metabolic benefit among individuals (Roy & Stefanyshyn, 2006; D. Stefanyshyn & Fusco, 2004; Willwacher et al., 2014).

It is possible that variation in optimal stiffness is related to foot parameters such as foot muscle strength (Goldmann & Brüggemann, 2012; Willwacher et al., 2014), heel to forefoot length ratio (Baxter, Novack, Van Werkhoven, Pennell, & Piazza, 2012), and arch height (Williams, Davis, Scholz, Hamill, & Buchanan, 2004), which will affect the stiffness of the foot. Optimal stiffness variation may also be related to gait pattern differences between midfoot (MFS) and rearfoot (RFS) strikers. MFS runners demonstrate increased knee flexion and ankle plantar flexion, which could affect midfoot stiffness and influence their response to shoe stiffness (Bruening, Pohl, Takahashi, & Barrios, 2018). Foot-strike groups also differ in muscle activation patterns, which have been found to affect the magnitude of metabolic cost reduction in high stiffness shoes (Flores, Le Gendre, Rao, Verton, & Delattre, 2019).

Optimal stiffness may also vary with running speed. Peak GRF increases linearly with running speed (Keller et al., 1996; Kyröläinen, Belli, & Komi, 2001), which will aide foot muscles in bending a stiff shoe. Leg stiffness also increases as speed increases (Arampatzis, Brüggemann, & Metzler, 1999; Farley & González, 1996; Kim & Park, 2011), which may alter optimal stiffness for an individual due to the variation in muscle activity required.

The primary purpose of this study was to understand how optimal shoe stiffness and the associated metabolic benefit are affected by running speed. A secondary purpose was to examine the anatomical and biomechanical characteristics associated with individual variation in optimal stiffness. We hypothesized that optimal stiffness and the associated metabolic benefit would increase with speed and that there would be a correlation between optimal stiffness variation and the measured anatomical and biomechanical variables.

Methods

Shoe Conditions

Five carbon fiber plates of increasing stiffness were constructed by the researchers, with stiffness controlled by the number of carbon fiber layers used. These plates were embedded by the shoe manufacturer between the midsole and outsole of a Saucony Freedom shoe (Saucony, Boston, MA) (Figure 1). This created six shoe stiffness conditions, with the control shoe having no carbon fiber plate. Weight was not equalized between shoe conditions to allow testing to represent performance of a production shoe model. Shoes with a thicker carbon fiber plate were heavier (Table 1).

Shoe LBS was tested using a three-point bending protocol (Roy & Stefanyshyn, 2006). Using an Instron Universal Testing Machine (model 3345, Instron, Norwood, MA), a vertical force was applied to the widest portion of the shoe forefoot at a displacement rate of 16 mm/sec to a total displacement of 7.5 mm (Figure 2). The force required for this displacement was recorded over five trials and averaged between 5–6 mm displacement (Table 1).

Participants

Twenty-one experienced male runners were recruited from a university setting and local running community (mass = 67.1 ± 5.0 kg, height = 178.9cm ± 4.0 cm, age = 26.4 ± 8.4 years, American shoe size 10–11.5). Subjects were required to have run 10 km in 36:00 min within the past year, as well as be free from lower extremity injuries for the past 3 months. According to the university institutional review board protocol, written informed consent was obtained from each participant prior to participation in the study.

Anatomical Measures

Subject height, mass, and shoe size were recorded and dominant foot was determined (van Melick, Meddeler, Hoogeboom, Nijhuis-van der Sanden, & van Cingel, 2017). The subject's dominant foot was put into an Arch Height Measuring System (JAK Tool & Model, Matawan, NJ) while sitting and standing to measure forefoot length, arch height index, and arch rigidity (Butler, Hillstrom, Song, Richards, & Davis, 2008). The Achilles tendon moment arm was defined according to Scholz et al. and averaged from standing medial and lateral measurements (Lundberg, Svensson, Nemeth, & Selvik, 1989; Scholz, Bobbert, van Soest, Clark, & van Heerden, 2008).

Toe flexion strength was measured using a previously published toe flexion strength measurement device (Brigham Young University, Provo, UT) and protocol (Ridge, Myrer, Olsen, Jurgensmeier, & Johnson, 2017). Strength was taken of the hallux separately, and then of second, third and fourth toes collectively. Peak toe flexion force from these procedures was used for analysis.

Testing Procedure

Using a randomized crossover design, a fast speed (4.47 m/s or 6:02 min/mile) or slow speed (2.98 m/s or 9:01 min/mile) was assigned to day one or two of testing for each subject. Within each day of testing, subjects were also assigned a random shoe testing order. To ensure accurate data collection, subjects were blind to shoe condition order.

Subjects warmed up on a force instrumented treadmill (Bertec, Columbus, OH) for 5 min at a self-selected pace in their own shoes. After the warm-up, to allow familiarization, subjects ran 3 min at testing speed (4.47 m/s or 2.98 m/s) while wearing equipment to measure metabolic data (COSMED Portable Metabolic System, Rome, Italy). Subjects then ran a 5-min trial in each shoe condition at testing speed, followed by a 2-min break. Previous research has found 2 min adequate to adjust metabolically and mechanically to a new shoe condition (Hunter et al., 2019). Metabolic ($\dot{VO}_2$) data was collected for the last 3 min of each trial, and a median measurement was recorded. Kinetic (peak GRF, centre of pressure anterior displacement, braking impulse, propulsive impulse) and kinematic (ground time) data were collected and averaged for 30 seconds starting at min 4 of each trial. Peak GRF was normalized by subject weight. Centre of pressure anterior displacement was measured from initial foot contact (vertical force greater than 100 N) until the termination of stance (vertical force less than 100 N). During the trial, high speed video (120 Hz) was also collected using a laterally placed camera (Sony A7S II, Tokyo, Japan) to classify foot-strike type (RFS vs. MFS).

Following collection, metabolic data was scaled to account for the varying mass of the shoe conditions (Table 1), using 100 g added shoe mass equals a 1.11% increase in metabolic cost (Hoogkamer, Kipp, Spiering, & Kram, 2016). A second order polynomial was fitted to each subject's data separately for each speed (Figure 3). The low point of the curve was recorded as the subject's optimal shoe stiffness, and the percent metabolic benefit from the control shoe was calculated from this point. If the curve indicated a subject's optimal stiffness was below or above the shoe conditions provided in this study, the lowest or highest stiffness condition was reported as optimal stiffness.

Statistical Analysis

After testing for normality, two separate Wilcoxon Signed-Rank Tests were used to assess differences in optimal stiffness and percent metabolic benefit at optimal stiffness (compared to the control shoe), between fast and slow speeds.

An additional set of Wilcoxon Signed-Rank Tests was used to compare values of optimal stiffness and percent metabolic benefit at optimal stiffness between foot-strike groups at both testing speeds. An independent sample t-test was used to compare variables (optimal stiffness, metabolic benefit, biomechanical variables) between foot-strike groups. For all procedures, an alpha level of .05 was used to test significance.

A stepwise linear regression was used to determine correlations between anatomical/biomechanical variables and optimal stiffness. This was done separately for the fast and slow speeds. A stepwise linear regression was also used to determine correlations between anatomical/biomechanical variables and percent metabolic benefit from control (at optimal stiffness). This was also done separately for each speed.

A regression curve was created per speed to examine changes in energy benefit with increasing shoe stiffness. Only subjects whose optimal stiffness fell within the range provided were included in these regressions.

Results

Optimal Stiffness

Across all subjects, average optimal stiffness was 19.29 N/mm (± 5.62) at the fast speed (4.47 m/s) and 17.04 N/mm (± 6.09) at the slow speed (2.98m/s). However, there was no significant change in optimal stiffness as speed increased (p = .147).

Metabolic Energy Benefit at Optimal Stiffness

At the fast speed (4.47 m/s), subjects demonstrated on average a 3.02% (± 2.62%) metabolic cost reduction at optimal stiffness when compared to the control shoe. At the slow speed (2.98m/s), this metabolic cost reduction was 1.93% (± 1.82%) compared to the control shoe. There was no significant change in metabolic benefit at optimal stiffness as speed increased (p = .144).

Foot-Strike Effect on Optimal Stiffness and Metabolic Energy Benefit

RFS demonstrated a significant change in optimal stiffness and the associated metabolic benefit with an increase in speed (p = .020, p = .024, respectively) (Table 2). MFS did not demonstrate a significant change in optimal stiffness or the associated metabolic benefit with an increase in speed (p = .395, p = .382, respectively) (Table 2).

There was no significant difference in optimal stiffness values at the fast speed or slow speed (compared separately) between RFS and MFS groups (p = .343, p = .188, respectively). There was also no significant difference in optimal stiffness metabolic benefit at the fast speed or slow speed between RFS and MFS groups (p = .698, p = .627, respectively).

Correlation with Subject-Specific Variables

There was no correlation between the measured anatomical or biomechanical variables and optimal stiffness. See Table 3 for variation in anatomical measurements.

Regression Curve of Shoe Stiffness Versus Metabolic Energy Cost

At the fast speed, the regression curve of shoe stiffness vs. metabolic energy cost was near significance (p = .054) (energy benefit = 6.289 − 1.056(shoe stiffness) + .031(shoe stiffness)^2). The slow speed regression was not significant (p = .194) (energy benefit = 4.989 − .821(shoe stiffness) + .024(shoe stiffness)^2). Only subjects whose optimal stiffness was predicted within the range of conditions provided were included in these regressions, this included 8 subjects at the fast speed, and 8 subjects at the slow speed.

Discussion

Effect of Running Speed on Optimal Stiffness and Percent Metabolic Energy Benefit

The primary purpose of this study was to examine changes in optimal stiffness and the associated metabolic energy benefit across two speeds. In our subject population, only RFS runners demonstrated a significant change in optimal stiffness and metabolic benefit between the slow (2.98 m/s) and fast speeds (4.47 m/s). We propose two main reasons for this difference.

First, gait patterns are fundamentally different between RFS and MFS runners. MFS runners demonstrate higher knee flexion and a more plantar-flexed and inverted ankle at initial foot contact, which could affect midfoot stiffness in early stance (Bruening et al., 2018). MFS runners also demonstrate increased late stance MTP joint extension, as well as increased positive and negative MTP joint work (Bruening et al., 2018). Since both foot-strike type and shoe stiffness affect midfoot stiffness and MTP joint mechanics (Bruening et al., 2018; Ferris, Liang, & Farley, 1999; Madden et al., 2016), interactions between the two are possible.

Second, muscle activations differ between foot-strike types. Individuals who adapt to increased shoe stiffness with increased proximal leg muscle activation during the braking phase of gait have been found to demonstrate higher metabolic cost reduction compared to individuals who adopt increased distal leg muscle activations (Flores et al., 2019). Runners who demonstrate greater ankle dorsiflexion and lower ankle plantar flexion react more economically to high stiffness shoes (Flores et al., 2019). RFS runners demonstrate higher work about the knee joint (proximal leg muscle activations) (Bruening et al., 2018) and more ankle dorsiflexion than MFS individuals, so it follows that they may react more favorably to a high stiffness shoe.

These differences between foot-strike patterns suggest several possible applications. For MFS runners, a single optimally stiff shoe should enable optimal performance regardless of the speed they run. However, to enable optimal performance for RFS runner, a higher stiffness shoe may be needed as speed increases. RFS runners will also receive a higher metabolic benefit when running fast in an optimally stiff shoe compared to a slow speed. Additionally, RFS runners capable of running faster speeds will receive a greater metabolic benefit than those capable of slower speeds.

Performance

The slow and fast speeds used in this study were vastly different (2.98 m/s and 4.47 m/s); however, they effectively highlighted the change in optimal stiffness with speed for RFS. It is doubtful, however, that individuals capable of running comfortably at the fast testing speed would ever do workouts or races close to the slow testing speed. In practicality, differences in speed between workouts and races would be small, so the change in a RFS runner's optimal stiffness and metabolic benefit would be much smaller than that noted between the 2.98 m/s and 4.47 m/s pace. It is likely that a single optimal shoe stiffness would suffice for RFS to provide optimal performance in both training and racing.

The value of an optimally stiff shoe may depend on the performance situation. On average, subjects demonstrated a metabolic benefit at optimal shoe stiffness of 3.02% at the fast speed and 1.93% at the slow speed. Changes in metabolic cost translate to slightly smaller percent changes in running velocity/performance. Though tested at different speeds than this study, Hoogkamer et al. (2016) observed that a 1.11% increase in metabolic cost results in a .78% increase in average running velocity. While the percent benefit in running velocity is relatively low, there are times when even a few seconds improvement is very important in a race performance.

Shoe Construction

Optimal stiffness metabolic energy benefit at both speeds was similar to that found in a study by Madden et al. (2016) but was between 1.6 to 3.0 times higher than the energy benefit reported by Oh and Park (2017) and Roy and Stefanyshyn (2006). While there were differences in testing speeds among these studies, our results suggest that for most runners, speed is not likely a substantial factor affecting shoe stiffness economic benefit. Instead, this difference may be due to shoe construction. Similar to Madden et al. (2016), shoe conditions for this study were built with the stiff plate inserted between the shoe midsole and outsole to preserve a higher level of subject comfort. This construction differs from the studies by Oh and Park (2017) and Roy and Stefanyshyn (2006), who both placed the stiff plate directly under the foot. It is therefore possible that the higher metabolic benefit found in this study and by Madden et al. (2016) is due to the comfortable and familiar construction of the shoes. In support of this conclusion, research has found a .7–1.9% improvement in running economy when wearing shoes rated as 'comfortable' when compared to less comfortable options (Luo et al., 2009).

Optimal Stiffness Variation Between Individuals

Variation in optimal stiffness was not found to be correlated with any of the measured anatomical or biomechanical variables. It is possible that the variation in optimal stiffness was instead related to differences in gait and muscle activation patterns. Flores et al. (2019) reported that individuals who responded economically to high shoe stiffness altered their gait to adopt more proximal (vastus medialis) rather than distal (tibialis anterior, gastrocnemius medialis) muscle activation during the braking phase. These responding individuals minimized muscle contributions about the ankle and demonstrated greater leg stiffness. Similarly, Madden et al. (2016) found individuals who responded economically to a stiff shoe to have decreased angular velocity at the ankle joint (decreased contribution of ankle muscles). This correlates with our finding that foot strike (which affects muscle activation) plays a part in an individual's response to shoe stiffness. Future research on this topic using motion capture and measuring muscle activation would be beneficial to further understand optimal stiffness variation.

Limitations

Several subjects presented data indicating their optimal shoe stiffness was outside of the range of shoe conditions provided in this study. For these subjects, the lowest or highest stiffness condition available was reported as optimal stiffness. Consequently, the reported averages for optimal stiffness and metabolic energy benefit only apply to the range of shoe stiffness conditions in this study (8.34–23.83 N/mm). It is, however, unlikely that running shoes would be created with stiffnesses very far outside of what was included in this study; subjects reported the stiffest shoe condition to feel extremely stiff.

An additional limitation relates to the construction of the shoe conditions and plates. Due to the manufacturing process, there was slight variation in shoe stiffness and mass per condition 1–6 across the four included shoe sizes. To account for this, slightly different shoe stiffnesses were used for each size and condition when correlating with metabolic cost. Metabolic data was also scaled according to the mass of each specific shoe condition to take out the effect of varying mass of metabolic cost.

Differences between the test shoe and each runner's typical running shoe may have affected individual responses. The test shoe (Saucony Freedom) had a four mm heel-toe drop and was fairly light-weight and flexible. Though we are confident that enough time was given to subjects to adjust biomechanically and metabolically to each stiffness condition (Ferris et al., 1999), it is possible that individuals accustomed to different shoe characteristics had developed lasting gait patterns that caused variation in their response to shoe stiffness.

Conclusion

Runners of all foot-strike patterns demonstrated an individualized optimal running shoe stiffness, with the metabolic benefit at this stiffness averaging 1.93–3.02% between the slow and fast speeds. This suggests that shoe construction needs to be personalized in regard to LBS when running economy is valued. For optimal performance, RFS runners may benefit from a higher stiffness shoe at a faster running speed.

Though optimal stiffness variation was not related to the measurements of anatomical and biomechanical characteristics taken in this study, further research including motion capture and muscle activation data could be beneficial to investigate this area further.

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Disclosure Statement

No potential conflict of interest was reported by the authors.

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Table 1. Mass Variation in Shoe Conditions 1–6

Shoe Condition	Mass (g)	Average Stiffness (N/mm)
Condition 1 (Control Shoe)	280–298.5	9.26
Condition 2	287–312	13.00
Condition 3	287–312	14.47
Condition 4	300–317.5	16.55
Condition 5	303.5–321	21.01
Condition 6	311.5–333	23.83

Mass variation within a condition is due to variation between size 10–11.5, with larger sizes weighing more.

Table 2. Foot-Strike Effect on Optimal Stiffness and Metabolic Benefit

	Rearfoot Strikers			Midfoot Strikers		
	Fast Speed	Slow Speed	p	Fast Speed	Slow Speed	p
Optimal Stiffness (N/mm)	20.54 ± 3.99	15.19 ± 5.69	.020	18.15 ± 6.77	18.73 ± 6.20	.395
Energy Benefit (% from control)	3.25% ± 1.56%	1.72% ± 2.07%	.024	2.80% ± 3.39%	2.11% ± 1.42%	.382

Comparisons are shown across fast (4.47 m/s) and slow (2.98 m/s) running speeds. P values reflect comparison within foot strike between fast- and slow-speed values. Rearfoot strikers demonstrated a significant change in optimal stiffness and the associated energy benefit between the fast and slow speeds.

Table 3. Variation in Anatomical Measurements Across Subject Population

Anatomical Variable	Mean ± SD
Mass (kg)	67.13 ± 4.99
Height (cm)	178.92 ± 3.99
Arch Height Index (Sitting)	.37 ± .05
Arch Height Index (Standing)	.34 ± .02
Heel to Forefoot Length Ratio	.38 ± .04
Toe Flexion Strength (Hallux) (N)	79.38 ± 37.43
Toe Flexion Strength (Lateral Toes) (N)	73.20 ± 24.44

Figure 1. Stiff Plate Placement in Training Shoe
A carbon fiber plate was inserted between the midsole and outsole of a Saucony Freedom shoe. The bottom image shows placement of this plate, covering the forefoot but not extending all the way to the heel.

Figure 2. Three-Point Bending Test

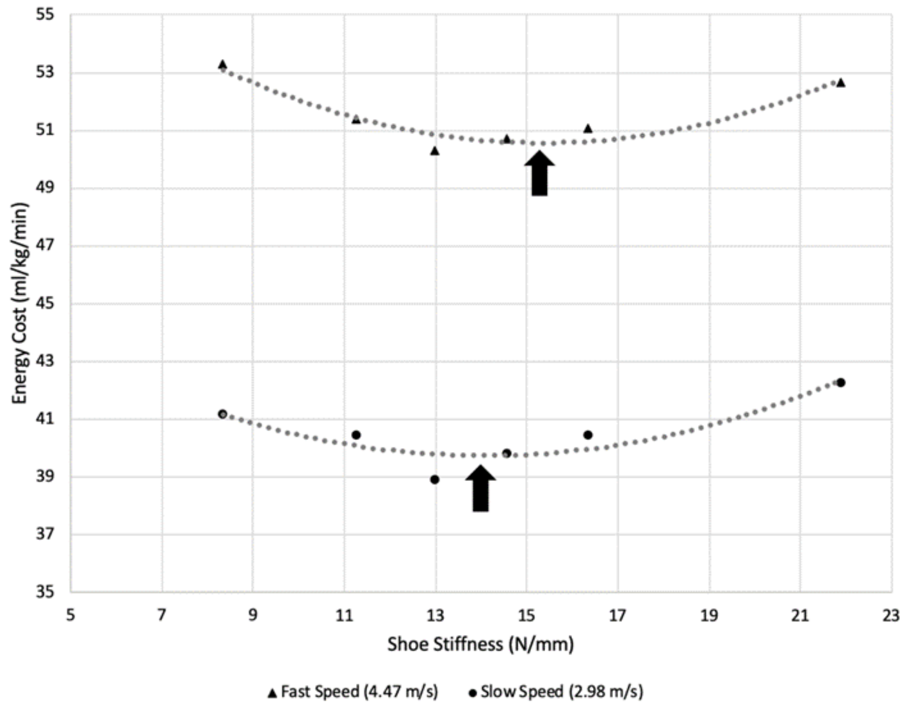

Figure 3. Shoe Stiffness vs. Metabolic Energy Cost for Single Subject
The low point of the curve (represented by the arrow) was recorded as the subject's optimal stiffness at that particular speed and allowed calculation of percent metabolic benefit from control shoe. For this particular subject, optimal stiffness at the fast speed was 15.36 N/mm and provided a 4.79% metabolic cost benefit compared to control. At the slow speed, optimal stiffness was 14.07 N/mm with a 3.44% metabolic benefit.