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Effects of midsole cushioning stiffness on Achilles tendon stretch during running

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Effects of midsole cushioning stiffness on Achilles tendon stretch during running

by

Michael Jonathan Stuart Esposito

A THESIS

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Abstract

Footwear midsole material can have a direct influence on running performance. However, the exact mechanism of improved performance remains unknown. It is speculated that changes to midsole stiffness may influence the energy return from the Achilles tendon, reducing the metabolic cost. The purpose of this study was to determine if changes in footwear midsole stiffness elicit changes in Achilles tendon stretch, and it was hypothesized that the footwear condition with better running economy for an individual will have greater Achilles tendon stretch.

Fourteen runners with personal best 10km times less than 40 minutes completed two testing sessions. Two footwear conditions were evaluated and consisted of a stiff and compliant midsole. Session one determined the moment arm of the Achilles tendon using dynamometer testing. Session two was a treadmill running session where kinetics, kinematics, metabolic and ultrasound data were collected while participants ran at a submaximal speed in each shoe condition. Main outcome variables were differences in Achilles tendon pseudo-stretch and differences in running economy, quantified as the energy cost of running. Correlation analysis was performed to assess the existence of a linear relationship between the variables.

There was a moderate positive correlation between the difference in pseudo-stretch and the difference in running economy, which was statistically significant ($r = 0.563$, $p = 0.036$, $d = 0.58$). Twelve participants had greater pseudo-stretch and better running economy in the same footwear condition and two participants did not have greater pseudo-stretch and better performance in the same footwear condition.

Based on estimates, the difference in energy returned from the Achilles tendon was 3.8 % on average of the mechanical energy required per step. Energy returns of this magnitude would be relevant and could cause the improved running economy observed. These results suggest that the energy returned from the Achilles could be a valid mechanism for improving running economy due to changes in footwear. These findings lead the way for future research to further understand the mechanism behind improved running economy. Understanding how footwear modifications affect internal mechanisms could have large ramifications on potential strategies for assisting and supporting locomotion.

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*“You better shave that thing when this is all finished...
you aren’t keeping that thing!”*

- Cassandra Carida

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List of Abbreviations and Symbols

Symbol	Definition
dB	Decibel
°	Degrees
PS _b	Difference in pseudo-stretch
EVA	Ethylene Vinyl Acetate
g	Grams
Hz	Hertz
J	Joules
kcal	Kilocalories
kg	Kilogram
kJ	Kilojoule
km	Kilometre
m	Metre
MHz	Mega Hertz
mL	Millilitre
mm	Millimetre
min	Minute
N	Newtons
r _{AT}	Moment arm of the Achilles tendon
M _{Ank}	Movement of the Achilles tendon at the ankle
M _{MTJ}	Movement of the myotendinous junction
PS	Pseudo-stretch
RE	Running economy
S	seconds

CHAPTER 1: INTRODUCTION

Running is a popular physical activity with over 55 million people participating in 2017 in the United States, and the number of participants has increased by 44% since 2006 (The Outdoor Industry Association, 2018). The large amount of participation in running creates a large market for running footwear. Running dates back centuries with events such as the modern Olympics showcasing running events since 1896. However, research on running footwear in a systematic and scientific manner didn't begin until the late 1970s (Cavanagh, 1980). With recent interest in running performance stemming from world records being set in the marathon for males and females, running footwear research has focused on the role of running footwear on running performance.

This research has shown that footwear modifications can have a direct influence on running performance (Frederick, 1984; Frederick et al., 1986; Hoogkamer et al., 2018; Roy and Stefanyshyn, 2006; Worobets et al., 2014). Footwear modifications that have been shown to influence performance include: bending stiffness, comfort, midsole material properties and mass. For example, an increase in mass of the shoe decreases performance (Frederick, 1984), while a softer and more resilient midsole of the shoe increases performance (Worobets et al., 2014). The current thesis focused on footwear midsole material properties. Midsole material properties were chosen since research has examined the effect of the midsole material on performance, with increased cushioning improving performance (Frederick et al., 1986; Worobets et al., 2014); however, the exact mechanism or mechanisms that facilitate this improved performance remain unknown.

Since the Achilles tendon plays a significant role in running (Lorimer and Hume, 2014), it is possible that a performance enhancing mechanism may involve influences on

the Achilles tendon. When running, elastic energy is thought to be stored within the muscle tendon unit and used to support and propel the body forward (Alexander, 1988; Fletcher and MacIntosh, 2015; Fukunaga et al., 2001; Ker et al., 1987). Also, the plantarflexor muscles are the largest contributor to mechanical work during running (Hamner and Delp, 2013; Stefanyshyn and Nigg, 1997), and the force generated by these muscles stretch the Achilles tendon. Previous research has shown that midsole hardness can influence the lower extremity muscle activation during running (Wakeling et al., 2002). Knowing this, it is reasonable to believe that the Achilles tendon mechanics may be influenced by footwear modifications and may be part of the mechanism responsible for the increases in performance previously observed. It is speculated that changes in midsole stiffness may change the amount of stretch of the Achilles tendon. A greater stretch of the Achilles tendon would allow for a greater energy storage and return from the tendon, and it is believed that this could result in a lower metabolic cost (i.e. an improved performance).

The purpose of this study was to determine if changes in footwear midsole stiffness elicit changes in Achilles tendon stretch, in an attempt to determine a mechanism behind running economy improvements previously observed with differences in footwear cushioning properties. It was hypothesized that the footwear condition with better running economy for an individual will have greater Achilles tendon stretch, suggesting greater energy storage and return of the Achilles tendon, during running.

Many theories and much speculation exist as to how modifications to footwear can improve performance; however, the exact mechanism or mechanisms remain unknown. This study investigated internal tendon changes due to external footwear modifications

(i.e. cushioning), which will aid in developing an understanding of how footwear can alter aspects of the musculoskeletal system for future work. Furthermore, understanding how footwear modifications affect internal mechanisms could have large ramifications on potential strategies for assisting and supporting locomotion.

This thesis contains six chapters. A brief introduction and the purpose of the study are presented in Chapter 1. Chapter 2 provides a review of the relevant research that informed the hypothesis of this thesis, which is stated at the end of the chapter. Chapter 3 is a description of the methodology used to determine running economy and Achilles tendon stretch, and the statistical analysis performed. Chapter 4 contains the results of the study, and Chapter 5 discusses the results in the context of the wider literature and the limitations of the study. Finally, Chapter 6 provides a summary of the study and presents future research directions.

CHAPTER 2: REVIEW OF RELEVANT LITERATURE

2.1 Running Economy

Running economy is defined as the rate of oxygen consumption when running at a given speed. Running economy has been established as a physiological measure of distance running performance (Cavanagh and Kram, 1985), and is representative of global metabolic energy expenditure (Conley and Krahenbuhl, 1980; Morgan et al., 1989). Improvements to running economy will result in improved distance running performance (Saunders et al., 2004), since a faster running speed can be achieved for the same physiological effort (Daniels, 1985). Previous research has used relative oxygen consumption ($\text{mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$) as a measure of running economy (Divert et al., 2008; Foster and Lucia, 2007; Hardin et al., 2004; Moore et al., 2014; Worobets et al., 2014). However, depending on the substrate metabolized, the energy equivalent for the volume of oxygen can vary (Lusk, 1928), and this method does not account for this. Other studies have used the oxygen cost per unit distance ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{km}^{-1}$) as a measure of running economy (Frederick et al., 1986; Lussiana et al., 2013; Perl et al., 2012). This method would allow for comparisons between groups running at different speeds. Similar to the previous method, this method does not account for the substrate use. It is known that substrate use changes with changes in running speed (Costill et al., 1979). Individuals running at different speeds could have different substrates used, meaning different energy available per liter of oxygen (Fletcher et al., 2009), therefore, this method may not be appropriate for comparison between groups. Other studies have used caloric unit cost ($\text{kcal} \cdot \text{kg}^{-1} \cdot \text{km}^{-1}$) or energy cost of running ($\text{kJ} \cdot \text{kg}^{-1} \cdot \text{km}^{-1}$) as a measure of running economy (Fletcher et al., 2009; Flores et al., 2019; Pialoux et al., 2008; Wunsch et al., 2017). Compared to the

other methods, this method takes into account the substrates used, using the respiratory exchange ratio as an indicator of the mix of carbohydrate and fat used (Fletcher et al., 2009). Research has shown running economy expressed as a caloric unit cost is more sensitive to changes in exercise intensity and, therefore, more appropriate than the other methods mentioned above (Fletcher et al., 2009). Figure 2.1 shows a figure from Fletcher et al. (2009) of caloric unit cost and oxygen cost per unit distance of running at three different speeds. Caloric unit cost increased significantly with speed, while there were no differences reported for oxygen cost per unit distance. For the current thesis, running economy was defined as the energy required to run a given distance. Regardless, research has shown that running economy can be influenced by footwear modifications.

Figure 2.1 Figure 1 from Fletcher et al. (2009). Caloric unit cost and oxygen unit cost of running at 75, 85, and 95% of the speed at lactate threshold.

2.2 Footwear Modifications

Recently, the impact of footwear on running economy has been a hot topic. For example, Nike's "Breaking 2" documentary in 2017 shows several athletes attempting to run a marathon in less than 2 hours, using footwear specifically designed (and proven) to

improve running economy. Footwear features that can be modified include, but are not limited to mass, bending stiffness, comfort and midsole material properties. Frederick (1984) first provided evidence that increasing shoe mass influences oxygen consumption with an increase in oxygen consumption of 1% for every 100 grams of mass added to each shoe. Then, Roy and Stefanyshyn (2006) found a mean energy savings of 1% when running in shoes with an increased midsole longitudinal bending stiffness. Luo et al. (2009) further found that improved shoe comfort may also improve oxygen consumption. Midsole materials with improved cushioning have been shown to have a direct influence on oxygen consumption, with improvements of up to 2.4% (Frederick et al., 1986). Research has also shown that combinations of these modifications can further increase performance. Hoogkamer et al. (2018) found a 4% decrease on average in metabolic cost when running in shoes with a combined stiff carbon fibre plate and a compliant and resilient midsole. Since midsole material with improved cushioning has shown to have the greatest improvements on its own, this was the focus of the current thesis.

2.3 Footwear Cushioning

Footwear cushioning has been a long-studied topic. Originally, changes to the cushioning of a midsole were introduced in attempt to reduce impact loading and reduce injury (Clarke et al., 1983; Hennig et al., 1996; Kaelin et al., 1985). In the mid 1980's, new cushioning materials, such as ethylene vinyl acetate (EVA), and unique cushioning systems, such as the Nike Air™ were developed specifically for running shoes to influence performance. Several studies have shown that footwear cushioning can influence performance. In the past, performance has been defined as lower oxygen

consumption while running. Bosco and Rusko (1983) found that running in a soft-soled shoe required more energy expenditure, and suggested that the footwear may modify the internal mechanical behaviour of the muscles and tendons, but mentioned that the exact mechanisms for the differences in performance are unknown. Frederick et al. (1986) showed an airbag system reduced the oxygen cost of running by 2.4% compared to traditional foam materials. Changes to the oxygen cost of running of this magnitude could reduce the current marathon world record time of 2:01:39 to approximately 1:59:42, based on predictions from Kipp et al. (2019). The airbag shoes had a higher deformation of the midsole and slightly higher energy return, as compared to traditional EVA foam, and the performance improvements are thought to be associated with the increased energy return. This can be explained by the *cost of cushioning* hypothesis (Frederick et al., 1983), stating that external cushioning may reduce the need of muscles for cushioning, resulting in reduced metabolic cost. Tung et al. (2014) provided clear support of this hypothesis, showing a reduced metabolic cost of approximately 1.5% when running on a cushioned surface (10mm) compared to a rigid surface. Further, Tung et al. (2014) suggested there to be an optimal cushioning thickness, as the metabolic cost on average was greater when the cushioning thickness was 20 mm compared to 10 mm thick (Figure 2.2).

Figure 2.2 Figure 3 from Tung et al. (2014). Metabolic power for different unshod cushioned surface conditions. The author suggested there is an optimal cushioning thickness.

Research has also shown evidence supporting the cost of cushioning hypothesis in footwear as well. Specifically, Worobets et al. (2014) had subjects run overground as well as on a treadmill in two shoe conditions, and in both overground and treadmill running, a softer and more resilient shoe decreased oxygen consumption by at least 1%. These shoes had significantly different mechanical properties (Figure 2.4), specifically differences in stiffness and energy lost. Additionally, Sinclair et al. (2016) and Sinclair and Dillon (2016) found oxygen consumption decreased 4.2% and 3.8% respectively on average when running in an improved energy return shoe (adidas Energy Boost) compared to a conventional running shoe. None of the previous three studies determined the mechanism linking the midsole properties and improved running economy, but it is possible that the cost of cushioning hypothesis may explain the changes observed. Further, Wunsch et al. (2015) found oxygen consumption decreased 2.1% on average when running in a shoe with a leaf spring structured midsole (Figure 2.3) compared to a standard foam midsole. The authors state that the midsole caused an increased anterior

foot shift, increased stride length, decreased stride frequency and a decrease in oxygen consumption.

Figure 2.4 Figure 2 from Worobets et al. (2014). Force-deformation curves for the footwear conditions used in the study. The soft shoe had a midsole that was less stiff and had lower energy loss.

Figure 2.3 Figure 1 from Wunsch et al. (2017). Leaf spring structured midsole (a) and a conventional foam shoe (b), and how the midsole is compressed under load.

Although there are multiple studies showing changes in midsole material can influence oxygen consumption, additional research has shown the influence of cushioning on oxygen consumption to be athlete specific (Nigg et al., 2003; Sinclair et al., 2013; Wunsch et al., 2017) with groups of subjects performing their best in different shoe

conditions. Wunsch et al. (2017) found the response to a leaf spring-structured midsole to be highly individual when compared to a standard foam shoe, contrary to their results found previously (Wunsch et al., 2015). Sinclair et al. (2013), found no group differences between shoes with different shock attenuating properties, but found individual differences in oxygen consumption of up to 2.75%. Nigg et al. (2003) found no group differences between shoe conditions, viscous or elastic heel, but about a quarter of the subjects had better performance with the viscous heel, and about a quarter had better performance with the elastic heel (Figure 2.5). Even though the viscous shoe had a greater amount of energy lost in the midsole (Figure 2.5), individuals still performed better in this condition despite greater energy loss from the midsole. Sinclair and Dillon (2016) found that running in a leaf spring structured midsole, specifically designed to increase the energy returned from the midsole (Sinclair and Dillon, 2016), creased oxygen consumption by 0.5% on average compared to a traditional running shoe. These results highlight that the energy returned from the midsole may not be fully responsible for improvements in oxygen consumption. Moreover, with changes in oxygen consumption appearing to be athlete specific, the cost of cushioning hypothesis may not fully explain performance improvements observed, suggesting there may be other internal mechanisms responsible for these improvements. However, there is no conclusive evidence of an internal mechanism to explain these performance improvements to date.

Figure 2.5 Figure 1 (left) and figure 4 (right) from Nigg et al. (2003). Figure 1 shows the force-deformation curves for both shoe conditions, and figure 4 shows the percent change in oxygen consumption for individual participants.

2.4 A Proposed Mechanism

Even though the internal mechanism resulting in the observed performance improvements is unknown, there is a general belief, and it is speculated that changes in footwear cushioning could influence the functioning of the Achilles tendon. When running, the Achilles tendon completes a stretch-shortening cycle during each step, where elastic strain energy is stored within the muscle-tendon unit, and is used to support and propel the body forward (Alexander, 1988; Fletcher and MacIntosh, 2015; Fukunaga et al., 2001; Ker et al., 1987). The storage and release of this elastic energy is thought to be important in maintaining a low energy cost of running (Fletcher and MacIntosh, 2015), by reducing the work required from the muscles (Voigt et al., 1995). Moreover, research has shown that individuals with a greater energy storage capacity of the Achilles tendon (calculated as the integral of the tendon force over the tendon strain) had better running performance (lower oxygen consumption) compared to others with a lower energy storage capacity (Figure 2.6) (Arampatzis et al., 2006). With the Achilles tendon having a significant role

during running, it is reasonable to believe that Achilles tendon mechanics may be influenced by footwear cushioning and may be part of the mechanism responsible for the performance improvements previously observed. Specifically, with footwear cushioning, it is speculated that when running with compliant cushioning, a lower heel position would occur, due to increased deformation of the midsole during stance. Due to this lower heel position, a greater extension of the Achilles tendon would occur. As a result, there would be greater energy storage and return from the Achilles tendon, which would result in a decreased work demand from the main plantarflexor muscles – gastrocnemius and soleus. Since the plantarflexor muscles are the largest contributors to mechanical work generated during running (Hamner and Delp, 2013; Stefanyshyn and Nigg, 1997), it is reasonable to believe that the overall result could be better running economy.

Figure 2.6 Figure 7 from Arampatzis et al. (2006). Energy storage capacity (left vertical axis) as a function of tendon force between group 1 and groups 2 & 3. Group 1 had significantly greater energy storage capacity and significantly better running economy running at 3.0, 3.5 and 4.0 m/s.

2.5 Hypothesis

The purpose of this study was to determine if changes in footwear midsole stiffness elicit changes in Achilles tendon stretch, in an attempt to determine a mechanism behind performance improvements previously observed with these differences in cushioning properties. It was hypothesized that the footwear condition with better running economy for an individual will have greater Achilles tendon stretch, suggesting greater energy storage and return of the Achilles tendon, during running.

CHAPTER 3: METHODOLOGY

3.1 Participants

Fourteen male participants with personal best 10 kilometer run times of less than 40 minutes were recruited for the study (Table 3.1). All participants properly fit into a US 9 shoe size and were free from lower extremity injuries within the previous three months. The sample size was based on calculations from previous treadmill oxygen consumption data (Worobets et al., 2014). Using this oxygen consumption data, a power analysis indicated 11 subjects were required ($\alpha = 0.05$, power = 0.8, $\delta = 0.46$, $\sigma = 0.49$) to detect a significant difference between footwear conditions, therefore, to ensure statistical power, 14 subjects were recruited. Individuals received verbal and written descriptions of the study design and informed written consent was obtained from all individuals prior to data collection in accordance with the Conjoint Health Research Ethics Board at the University of Calgary (REB18-0924).

Table 3.1 Characteristics of the fourteen participants recruited for the study.

Participant	Age	Height [m]	Mass [kg]	Running Speed [m/s]
1	30	1.75	78.9	3.35
2	30	1.75	63.0	3.80
3	31	1.68	69.5	3.35
4	29	1.76	77.3	3.35
5	27	1.68	54.7	3.58
6	21	1.66	60.2	4.02
7	19	1.76	61.2	4.92
8	30	1.71	64.3	3.35
9	30	1.87	80.2	4.02
10	39	1.78	61.0	3.58
11	19	1.72	61.5	4.47
12	20	1.77	77.4	3.35
13	20	1.76	65.2	3.80
14	21	1.85	75.6	4.25
Mean	26.1	1.75	67.9	3.80

3.2 Footwear

Two footwear conditions were used – stiff and compliant (Figure 3.1). The stiff shoe had a midsole made of EVA and the compliant shoe's midsole was made of expanded thermoplastic polyurethane pellets (Boost™). Concerted effort was made to construct the shoes such that they were identical in every aspect except for the midsole cushioning material. With the different midsole materials, the shoes had a difference in mass (Table 3.2); therefore, the shoes were matched in mass by evenly distributing lead weights near the center of mass of the stiff shoe to eliminate any potential confounding effect of mass. These two shoes were chosen since previous research has used footwear with similar differences in cushioning stiffness and observed differences in running economy of 1% on average between footwear conditions (Worobets et al., 2014).

Figure 3.1 Photograph of the footwear conditions used in the study. The Stiff condition was made with a midsole consisting of EVA and the Compliant condition had a midsole consisting of thermoplastic polyurethane Boost material.

3.3 Footwear Mechanical Testing

Rearfoot cushioning stiffness and energy loss of the footwear was measured using a previously published protocol (Worobets et al., 2014). Briefly, each shoe was fitted with a rigid shoe last and mounted onto a force transducer of a servo-hydraulic testing system (MTS 858 Mini Bionix II test system, Minneapolis, USA) (Figure 3.2). Each shoe condition was subjected to three test sessions with each session consisting of 20 consecutive loading and unloading cycles. Each cycle consisted of the shoe being compressed at a rate of 4250 N/s until a maximal load of 1700 N was reached, then the shoe was unloaded. These values were chosen because they represent loading rate and peak force during running (Worobets et al., 2014). The stiffness of each midsole was determined by calculating the slope of a line of best fit to the loading curve. Energy lost by the midsole was calculated from the following equation:

$$E_{Lost} = \left(1 - \frac{E_R}{E_A}\right) * 100\% \quad (1)$$

where E_R is the energy returned by the midsole (represented by the area under the unloading curve) and E_A is the energy absorbed by the midsole (represented by the area under the loading curve). For each shoe, average stiffness and hysteresis values were calculated using the 20th loading-unloading cycle from each of the three test sessions and averaged. Force-deformation curves of the two shoe conditions are shown in Figure 3.3 and calculated stiffness and energy loss values are shown in Table 3.2.

Table 3.2 Mechanical properties of the shoes used in the study.

	Stiff	Compliant
Mass [g]	311	322
Rearfoot Cushioning Stiffness [N/mm]	226	179
Energy Loss [%]	26.2	18.1

Figure 3.2 Photo of the mechanical testing setup.

Figure 3.3 Force-deformation curves of each of the footwear conditions.

3.4 Data Collection

Testing was completed during two sessions. The objective of session one was to measure Achilles tendon moment arm, using a previously published method (Fletcher et al., 2010). Participants laid prone with their knee at 180° (straight leg) and their ankle at 90° in a dynamometer (Cybex NORM, Humac, CA, USA). The axis of rotation of the Cybex was aligned with the ankle joint, while the participant's left foot was secured using Velcro straps. Then, participants were fitted with an ultrasound probe. The ultrasound probe (LV8-5N60-A2 transducer, ArtUs EXT-1H, Telemed, Lithuania) was positioned to measure the movement of the myotendinous junction of the left medial gastrocnemius (Figure 3.4). A copper wire was placed on the skin underneath the ultrasound probe. The wire was visible in the ultrasound field of view and was used to determine if the probe moved during the testing session. The probe was placed in a custom 3D printed holder, designed to prevent the probe from rotating off the skin, and was held in place with athletic wrap and gaffer tape. To determine the moment arm of the Achilles tendon, the ankle was passively rotated in the Cybex from 30° to 0° plantarflexion at $5^\circ/\text{s}$. Three repetitions served as conditioning trials, and on the fourth trial, ultrasound images were recorded.

Figure 3.4 Ultrasound probe location on the left medial gastrocnemius (MG) (left) and a labelled ultrasound image (right).

Session two was a treadmill running session and was conducted on an instrumented treadmill (Bertec Corporation, Columbus, USA) set at a 1° incline to mimic outdoor running (Jones and Doust, 1996). The protocol for session two was adapted from previously published methods (Roy and Stefanyshyn, 2006). First, height, mass and left leg anthropometric measurements (thigh length, thigh circumference, calf length, calf circumference, foot length, foot breadth, malleolus height and malleolus width) were recorded. After the measurements were recorded, participants were fitted with the ultrasound probe in the same position as session one. After the ultrasound probe was secured, the test session began with an incremental running test to a submaximal intensity to approximate at which speed the participant would reach their anaerobic threshold. A metabolic cart (Cosmed, Rome, Italy) was used to measure breath-by-breath pulmonary gas exchanges. Participants started the test at 2.46 m/s and the speed increased 0.22 m/s every two minutes. The incremental test continued until each athlete reached their anaerobic threshold (via monitoring of the real-time Cosmed output). Anaerobic threshold was visually identified from the real-time data feed by looking for a combination of excessive CO₂ production (Beaver et al., 2017), a value of respiratory exchange ratio greater than 1 (Solberg et al., 2005) and a non-linear increase in pulmonary ventilation. The anaerobic threshold was used to determine the submaximal running speed for the testing session, and ensure the speed was relative to each participant's fitness level. The ultrasound probe was attached during the incremental test, allowing subjects to adapt to running with the probe prior to data collection. However, no kinematic, kinetic, or ultrasound data were recorded during the incremental test. The incremental test also allowed each participant to warm up prior to data collection, and

participants were given a 10-minute rest following completion of the incremental test before the running trials.

During the running trials, kinematic, kinetic, metabolic and ultrasound data were collected. Kinematic data were measured with the use of an 8-camera motion analysis system (200 Hz) (Vicon Motion Systems Ltd., Oxford, UK). Twenty-six retroreflective markers were placed on each participant and used to track the motion of the pelvis, thigh, shank, rearfoot, and forefoot through space. The marker positions consisted of eight anatomical landmark markers and eighteen tracking markers. The anatomical landmark markers were placed on the left and right greater trochanter, left medial and lateral femoral condyles, left medial and lateral malleoli, left 1st metatarsal, and the left 5th metatarsal. The tracking markers included a marker on the left and right anterior superior iliac crest, a marker on each of the left and right posterior superior iliac crest, a cluster of four markers placed on the left anterior thigh, a cluster of four markers placed on the left lateral shank, a cluster of three markers placed on the forefoot and a cluster of three markers placed on the rearfoot aspects of the shoe. Ground reaction force data were obtained through an instrumented treadmill (1000 Hz), and metabolic data were recorded breath by breath using the metabolic cart. The ultrasound (177 Hz) was recorded with the following settings: Depth: 30mm, Dynamic Range: 72 dB, Power: -3 dB, Frequency: 8 MHz. A schematic of the participant with all equipment can be seen in Figure 3.5.

Figure 3.5 Schematic views of the back (left), side (middle) and front (right) view of the participant with all equipment attached during the running trials (motion capture markers, ultrasound probe and breathing mask). The grey markers remained on while the blue markers were removed during the running trials.

Once all the markers were attached, a static motion capture trial was recorded prior to the running trials to determine joint centers; the greater trochanter, femoral condyle, malleoli, and metatarsal markers were subsequently removed for the running trials. Participants performed two 6-minute steady state running trials at a submaximal running speed, one in each shoe condition in a random order. The running speed of the trials was determined from the incremental test, 0.22 m/s slower than the final speed of the incremental test, to ensure the participant was running at a speed below their anaerobic threshold. The first four minutes of the running trial allowed the participant to reach a steady-state of oxygen consumption (Morgan et al., 1989), and data from all systems (kinematics, kinetics, metabolic and ultrasound) were recorded during the final

two minutes of the trial. Steady-state was determined by a respiratory exchange ratio of less than 1.0 and by a visual inspection and confirmation of a plateau of oxygen consumption over the final two minutes of the trial (Sims et al., 2018). Participants were given a 10-minute rest following completion of the first running trial before undertaking the second running trial.

3.5 Data Analysis

3.5.1 Metabolic Data

Running economy ($\text{kJ}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) was calculated from the equation presented by Fletcher et al. (2010) and was calculated as the average of every breath during the final 2 minutes of the trial. Running Economy was calculated from the following equation:

$$RE = EE * 4.1839 \frac{\text{kJ}}{\text{kcal}} * S^{-1} * BM^{-1} * 1000 \frac{\text{m}}{\text{km}} \quad (2)$$

where EE is the energy expenditure in kcal/min (outputted by the Cosmed), S is the speed in m/min and BM is body mass in kg. Lower running economy would indicate a better running economy.

3.5.2 Kinematic Data

Kinematic data were analyzed using Visual 3D software (v2020.07.02, C-Motion, Germantown, MD, USA). Ground reaction force and kinematic data were smoothed using a zero-lag low-pass 4th order Butterworth filter with a cut-off frequency of 50 Hz. A 20-N threshold for the vertical ground reaction force was used to identify the stance phase of running, and thirty strides for the left leg were extracted for the analysis of each shoe

condition. The joint center for the ankle was determined as the midpoint between the lateral and medial malleoli markers in the neutral trial. Cardan angles were calculated for the ankle joint with a flexion-extension, abduction-adduction, and internal-external rotation sequence (Wu et al., 2002). Movement of the Achilles tendon at the ankle (M_{Ank}) was calculated from the following equation:

$$M_{Ank} = r_{AT} \tan \theta \quad (3)$$

where r_{AT} is the Achilles tendon moment arm and θ is the dorsiflexion angle relative to the ankle angle during the static trial.

3.5.3 Ultrasound Data

The ultrasound images were post-processed using ImageJ (National Institutes of Health, Bethesda, MD, USA). The contrast and brightness were all adjusted using ImageJ. This was done to enhance the contrast between the muscle tissue and the aponeurosis of the muscle (Figure 3.6). From session one, the Achilles tendon moment arm was calculated using the tendon excursion method (Fath et al., 2010) from when the ankle was passively rotated from 30° to 0° plantarflexion. Briefly, the Achilles tendon moment arm was calculated from the following equation:

$$r_{AT} = \frac{dL}{d\theta} \quad (4)$$

where dL is displacement of the myotendinous junction caused by rotating the ankle from 30° to 0° plantarflexion in millimetres and $d\theta$ is the range of rotation in radians. Myotendinous junction displacement was quantified in ImageJ and displacement measured was converted from pixels to millimeters from the scale determined in ImageJ,

which was 11.2 pixels per millimeter. The moment arm was then adjusted to account for differences in values obtained from the tendon excursion method and the center of rotation method based on data from Fath et al. (2010). There is no gold standard for moment arm measurement, but it has been shown that tendon excursion method results in smaller moment arm estimate by an average of 15 mm compared to the center of rotation method (Fath et al., 2010).

Figure 3.6 Example of ultrasound image before (top) and after (bottom) post-processing in ImageJ.

From the ultrasound images recorded during the running trials, movement of the myotendinous junction (M_{MTJ}) was measured as the distance between the copper wire position and the most proximal myotendinous junction position. All distances were measured thirty times per condition and the distances measured were converted from pixels to millimeters.

3.5.4 Energy Estimations & Relation to Running Economy

Pseudo-stretch of the Achilles (PS) was calculated by adding M_{Ank} and M_{MTJ} together for each footwear condition. The variable was termed “pseudo-stretch” since the true stretch of the tendon cannot be determined, and it was used to find differences between conditions. The true stretch of the tendon cannot be determined since the length of the tendon was not measured during the run. The difference in PS (PS_D) was calculated as PS in the stiff condition minus PS in the compliant condition. PS_D was used to make assumptions about which shoe condition had greater Achilles tendon stretch. It was assumed that the shoe condition with greater PS would have greater energy storage and return of the Achilles tendon. Differences in running economy were calculated as the percent difference between conditions from the following equation:

$$\Delta RE = \left(\frac{RE_{compliant} - RE_{stiff}}{\left(\frac{RE_{compliant} + RE_{stiff}}{2} \right)} \right) * 100\% \quad (5)$$

There was a change in order in the difference calculation between running economy and pseudo-stretch calculations (compliant minus stiff vs stiff minus compliant) so that the final values direction would align, positive values indicating more stretch and better running in the stiff condition and negative values for the compliant condition. PS was correlated with differences in running economy to determine if a relationship existed.

3.5.5 Statistics

All statistical analysis was done using SPSS (v26, IBM, Armonk, NY, USA) and values of p less than 0.05 were considered statistically significant. The Shapiro-Wilk test was performed to confirm that the variables (M_{Ank} , M_{MTJ} and RE) in each shoe condition

were normally distributed. Based on the assumption that the distributions were normal, Pearson correlation analysis was performed to assess the existence of a linear relationship between running economy and pseudo-stretch measurements.

CHAPTER 4: RESULTS

Participant values with group means and standard deviations for the variables are shown in Table 4.1. Differences in pseudo-stretch had a mean of -0.1 mm with a range of -5.7 to 3.4 mm, while differences in running economy had a mean of -0.83% with a range of -4.57% to 4.33%. A Shapiro-Wilk test confirmed that the data (M_{Ank} , M_{MTJ} , and RE) were normally distributed ($p \geq 0.552$) (Table 4.2), therefore, parametric tests were performed. There was a moderate (Schober and Schwarte, 2018) positive correlation between the difference in pseudo-stretch and the difference in running economy, which was statistically significant ($r = 0.563$, $p = 0.036$, $d = 0.58$) (Figure 4.1). Positive values for difference in pseudo-stretch and difference in running economy indicate a greater stretch and better running economy, respectively, in the stiff shoe condition. Twelve participants had greater pseudo-stretch and better running economy in the same footwear condition and two participants (P2, P12) did not have greater pseudo-stretch and better running economy in the same footwear condition.

Table 4.1 Participant values, group mean and standard deviations for movement of the Achilles tendon at the ankle (M_{Ank}), movement of the Achilles tendon at the myotendinous junction (M_{MTJ}), difference in pseudo-stretch (PS_D), running economy (RE) and difference in running economy (ΔRE).

	M_{Ank} [mm]		M_{MTJ} [mm]		PS_D [mm]	RE [$\text{kJ} \cdot \text{kg}^{-1} \cdot \text{km}^{-1}$]		ΔRE [%]
	Stiff	Compliant	Stiff	Compliant		Stiff	Compliant	
P1	16.3	18.1	8.0	11.9	-5.7	4.59	4.47	-2.52
P2	19.6	19.2	30.6	29.7	1.3	4.75	4.72	-0.76
P3	18.9	18.5	25.6	26.7	-0.6	5.09	4.87	-4.33
P4	23.4	22.8	0.2	1.9	-1.1	4.79	4.67	-2.51
P5	18.2	19.6	17.7	17.8	-1.5	4.40	4.37	-0.70
P6	19.6	18.7	8.7	9.6	-0.1	5.04	4.98	-1.02
P7	20.9	20.1	19.4	18.5	1.6	4.39	4.60	4.57
P8	17.9	17.5	9.7	6.8	3.4	4.64	4.74	2.10
P9	19.4	20.4	18.8	18.9	-1.0	4.37	4.30	-1.55
P10	24.5	25.2	13.9	14.2	-1.0	4.40	4.22	-4.03
P11	22.9	21.9	15.9	15.6	1.2	3.94	4.00	1.49
P12	21.7	20.5	5.3	5.8	0.7	4.93	4.76	-3.44
P13	22.0	21.7	22.1	22.1	0.3	4.71	4.73	0.44
P14	21.4	21.8	1.2	0.4	0.4	4.41	4.44	0.70
Mean	20.5	20.4	14.1	14.3	-0.1	4.60	4.56	-0.83
SD	2.3	2.1	9.0	8.8	2.1	0.31	0.27	2.52

Table 4.2 Results from the Shapiro-Wilk test for each variable in each shoe condition.

	Stiff			Compliant		
	Statistic	df	p value	Statistic	df	p value
M _{Ank}	0.984	14	0.992	0.956	14	0.652
M _{MTJ}	0.976	14	0.945	0.976	14	0.946
RE	0.949	14	0.552	0.964	14	0.790

Figure 4.1 Difference in running economy versus difference in pseudo-stretch (red) and trendline for all fourteen participants (black). Positive values for difference in pseudo-stretch and difference in running economy indicate a greater stretch and better running economy respectively in the stiff shoe condition.

CHAPTER 5: DISCUSSION OF RELEVANT FINDINGS

The purpose of this study was to determine if changes in footwear cushioning stiffness can elicit changes in Achilles tendon stretch, in an attempt to determine a mechanism behind running economy improvements previously observed with differences in cushioning properties. It was hypothesized that the footwear condition with better running economy would have greater energy storage and return of the Achilles tendon, attributed to a greater Achilles tendon stretch during running. In partial support of the hypothesis, there was a moderate positive correlation between the difference in pseudo-stretch of the Achilles tendon and the difference in running economy between footwear conditions. This study was one of the first to determine a difference in Achilles tendon stretch due to footwear modifications and how they relate to running economy, providing valuable information for future studies.

The running economy results were consistent with previous studies (Nigg et al., 2003; Sinclair et al., 2013; Wunsch et al., 2017), with groups of subjects performing their best in different shoe conditions. In the present study, nine participants had their best running economy in the compliant footwear condition. These results suggest that the cost of cushioning hypothesis may not fully explain the running economy results observed, since this hypothesis would suggest that all participants would have their best running economy in the compliant footwear condition due to the mechanical properties of the midsole. This is not to say that cushioning was not involved, but this theory may not fully explain running economy improvements observed, suggesting there may be other internal mechanisms responsible for these improvements. These results provide some initial

evidence that Achilles tendon stretch may be an internal mechanism partially responsible for the running economy improvements observed.

The results show a moderate positive correlation between the difference in running economy and the difference in pseudo-stretch; however, from this data, the absolute stretch of the tendon cannot be determined, and the energy stored and returned from the Achilles tendon is unknown. Intuitively, the footwear condition with greater stretch would have a greater energy storage and return from the tendon, but the difference in energy storage and return between conditions is unknown. Fletcher and MacIntosh (2015) estimated the energy returned from the Achilles tendon of trained males during running. The estimate from this study was chosen since the participants in the trained male group were a similar height and mass to the participants of the present study (Fletcher and MacIntosh 1.76m, 67.8kg; this study 1.75m, 67.9kg) and participants ran at a similar average speed (Fletcher and MacIntosh 3.64 m/s; this study 3.80 m/s). The energy returned from stretching the Achilles tendon was 42 J on average, ranging from 25 to 70 J (Figure 6 of Fletcher and MacIntosh, 2015). Based on this estimate (42 J), assuming the hysteresis to be 10% (Finni et al., 2013), approximately 22.3 mm of tendon stretch would occur each step. Exploring three values for increase in stretch, 0.1 mm (smallest difference in pseudo-stretch from this study, P6), 1.4 mm (absolute average of pseudo-stretch from this study) and 5.7 mm (greatest difference in pseudo-stretch from this study, P1), would result in a total tendon stretch of 22.4, 23.7, and 28.0 mm respectively. The estimated energy return from these tendon stretches are 42.4, 47.4 and 66.2 J, equating to an average difference of 5.4 J ranging from 0.4 to 24.4 J. The average mechanical energy for each step was estimated as 140 J, using mechanical power estimates from

Williams and Cavanagh (1987). Based on this, the difference in energy return from the Achilles tendon would result in an average of 3.9 % of the total mechanical energy required, ranging from 0.3 to 17.3 %. Energy returns of this magnitude would be relevant and could cause the improved running economy observed. These results suggest that the energy returned from the Achilles could be a valid mechanism for improving running economy due to changes in footwear.

The relationship between mechanical energy and metabolic energy is very complex (Williams and Cavanagh, 1987). Muscular efficiency, defined as the ratio of mechanical power to metabolic energy expenditure (Williams and Cavanagh, 1987), has been used to relate mechanical energy to metabolic energy. Using a muscular efficiency of 0.2 (Williams and Cavanagh, 1987), it is estimated that a mechanical energy return of 5.4 J would correspond to 27 J of metabolic energy. Using a metabolic cost of running of 850 J /stride (Fletcher and MacIntosh, 2015), 27 J would equate to a 3.18 % average change in metabolic energy, slightly greater than the metabolic changes of this study and previous studies examining metabolic changes due to footwear (Frederick et al., 1986; Tung et al., 2014; Worobets et al., 2014). Further, it is possible that the estimations of total Achilles tendon stretch were overestimated, based on previous studies showing smaller tendon stretch (Farris et al., 2012; Lai et al., 2018). Assuming stretch is overestimated by 50%, a 22.3 mm stretch would become 14.9 mm, returning approximately 18.8 J. Using the average increased stretch of 1.4 mm, the estimated energy return would be 22.5 J, a difference of 3.7 J and on average a total of 2.6 % of the mechanical energy required. This lower percentage of mechanical energy does not change the interpretation and it is believed the energy returned from the Achilles tendon

may be a valid mechanism in improving running economy with changes in footwear. The results provide some initial evidence of this mechanism, but further research is needed to fully understand this mechanism.

Although the results of the present study suggest that the energy returned by the Achilles tendon may be a valid mechanism, the possibility of other mechanisms cannot be discounted. The stretch of the Achilles tendon may result in changes to the function of the triceps surae. If the length change of the muscle tendon unit during a stride is taken up by stretching of the Achilles tendon, this allows for less shortening of the muscle fascicles and slower shortening velocity (Fukunaga et al., 2001; Ishikawa et al., 2007). Less shortening of the muscle fascicles allow for optimization of muscle activation and force-length-velocity properties (Fletcher et al., 2013). It is believed that the optimization of these relationships could result in a reduced metabolic cost, however, more research is required

In the present study, foot strike pattern was not controlled for. Interestingly, seven of the nine participants who performed better in the compliant condition were rearfoot strikers and four of the five participants who performed better in the stiff condition were mid or forefoot strikers. Strike type was determined based on ankle angle at foot contact, with rearfoot strikes having a dorsiflexed position at initial contact and midfoot or forefoot having a plantarflexed position (Nunns et al., 2013). It has been shown that foot strike pattern alone does not influence performance (Anderson et al., 2020), but it may be that runners with certain foot strike patterns combined with a certain midsole cushioning allows for an increased Achilles tendon stretch, leading to an improved performance. Further, the average mass of participants that performed better in the compliant condition

was greater than the mass of participants that performed better in the stiff condition (Compliant: 69.2 kg, Stiff: 65.5 kg). The greater mass on the compliant midsole may increase the deformation of the midsole, allowing for greater energy returned from the midsole during a stride, and potentially increased stretch of the Achilles tendon. Differences between running economy groups was not part of the objectives of the current study and were not pursued any further, so more investigation is required to test these speculations.

5.1 Limitations

There are a few limitations that should be noted. Absolute tendon stretch was not calculated. Without absolute tendon stretch, energy storage and return values of the Achilles tendon can only be estimated. In this study, the difference of tendon movement between conditions was calculated, and it is believed that this difference would equal the difference in stretch between conditions. This data set shows that changes to footwear cushioning may be able to elicit changes in Achilles tendon stretch, and further research is needed to determine the exact energy savings related to the increase in stretch. Another limitation is that the ultrasound may have been slightly obtrusive for the runner. This may translate to an 'atypical' running pattern, and any changes in running kinematics seen may be caused by the addition of the probe. This being said, it is believed with the ultrasound probe design (cord parallel to the scanning surface), this effect would be minimal. Also, the addition of the ultrasound probe may increase running economy. This study had a within-subject design, therefore, the difference in running economy is more relevant than the absolute value of running economy.

CHAPTER 6: CONCLUSION

6.1 Summary of the Study

The purpose of this study was to determine if changes in footwear cushioning stiffness can elicit changes in Achilles tendon stretch, in an attempt to determine the mechanism behind running economy improvements previously observed with differences in cushioning properties. It was hypothesized that the footwear condition with better running economy would have greater energy storage and return of the Achilles tendon and this could be attributed to a greater Achilles tendon stretch during running. Participants ran while Achilles tendon movement, ankle kinematics and oxygen consumption were measured in a stiff and compliant midsole footwear condition. There was a positive moderate correlation between difference in running economy and difference in pseudo-stretch of the Achilles tendon, which was statistically significant ($r = 0.577$, $p = 0.031$).

Based on the running economy results, with eight participants having their best running economy in the compliant footwear condition and six in the stiff condition, previous theories (cost of cushioning) may not be able to fully explain the improved running economy, and another internal mechanism may be responsible. The average difference in energy returned by the Achilles tendon was 5.4 J, which was 3.9 % of the total mechanical energy required. Energy return of this magnitude would be relevant and could cause the improved running economy observed. Further, it is approximated that the energy returned by the Achilles tendon would equate to 3.18 % of the metabolic energy, slightly greater than the findings of the metabolic savings found from the metabolic data of the study. The results suggest that the energy returned from the Achilles may be a valid

mechanism for improving running economy with changes in footwear cushioning. These findings have given direction to future research.

6.2 Future Directions

The findings of this research are stepping stones to future research. Future research should measure absolute Achilles tendon stretch when running in different footwear conditions to calculate energy storage and return values to determine if the estimates calculated here are accurate. Measuring Achilles tendon stretch can be done by tracking the position, using motion capture, of the calcaneus as well as the ultrasound probe during running to get an accurate measurement of tendon length. In addition, research should include larger sample sizes to identify groups of individuals that perform better in the different footwear conditions, in attempt to determine why some individuals perform better in a specific condition. Further, future research should empirically investigate what is happening at the tendon as well as the muscle, to see how the muscle tendon unit works together. This could provide evidence to see if Achilles tendon stretch is able to optimize the force-length-velocity relationship of the muscle. Finally, future research should investigate to see if a combination of footwear modifications has the same effect. For example, the Nike Vaporfly has a stiff carbon fibre plate and a compliant and resilient midsole cushioning and has shown to have an increase in performance of 4% on average. Research could investigate to see if the same mechanism is the cause of this improved running economy or if another mechanism is involved.

6.3 Final Remarks

This study investigated the effect of midsole cushioning on Achilles tendon stretch while running. It was speculated that increased stretch of the Achilles tendon would return more energy and result in an improved running economy. There was a positive moderate correlation between difference in running economy and difference in tendon stretch between footwear conditions. The difference in energy returned by the tendon was large enough to cause improvements to running economy. The results of this study suggest that energy returned by the Achilles tendon may be a valid mechanism to improve running economy. These findings lead the way for future research to further understand the mechanism behind improved running economy. Understanding how footwear modifications affect internal mechanisms could have large ramifications on potential strategies for assisting and supporting locomotion.

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APPENDIX A – Consent Form

Participant Consent Form

TITLE: External perturbations and internal mechanisms of locomotor performance

SPONSOR: Natural Sciences and Engineering Research Council of Canada (NSERC)

INVESTIGATORS: Dr. Darren Stefanyshyn, Dr. John Wannop
403-220-7003

This consent form is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Take the time to read this carefully and to understand any accompanying information. You will receive a copy of this form.

BACKGROUND

Footwear cushioning has been shown to influence running economy and running performance with modifications in cushioning leading to external changes in running kinematics, suggesting that internal musculoskeletal changes could be related to improved running economy. However, the mechanism of improved performance or the internal musculoskeletal changes that lead to improved performance remains unknown.

WHAT IS THE PURPOSE OF THE STUDY?

The main goal of this research project, is to determine the mechanisms behind the performance improvements both on a global and individual level and to better understand how manipulating these mechanisms influences performance.

WHAT WOULD I HAVE TO DO?

Prior to testing, you will be required to fill out a Physical Activity Readiness Questionnaire (PAR-Q). For the study you will perform running on a treadmill, while your motion and the forces you exert on the ground is recorded using a motion analysis system. Testing will be performed on two separate days with each day consisting of a similar protocol, with motion analysis data being recorded on one day and ultrasound measurements of the leg being performed on the other day.

During each of session, your motion and the forces exerted on your body will be measured using a motion capture system. Small reflective markers will be taped and glued to your body and these markers will be filmed by high speed video cameras, while the instrumented treadmill will measure the ground reaction force. During session two, internal imaging of your lower leg during running will be recorded using an ultrasound probe.

An additional testing session will also be conducted in which the strength measurements of the ankle joint musculature will be measured using a dynamometer. The ankle joint will be placed at

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specific angles, and you will be asked to maximally extend or contract the ankle joint. During these muscular contractions internal imaging of the lower leg will be recorded using an ultrasound probe.

The total duration of testing for each session should take approximately 60 minutes.

WHAT ARE THE RISKS?

The risks associated with the study would not be greater than those encountered by you during everyday life. You will participate in sport movements/activities that would be common during running. As with any sport activity a potential for suffering an injury is present, however, this risk will be minimized by providing adequate rest between trials and allowing the athletes to perform their conventional warm-up prior to testing. Participants might experience slight muscle soreness or discomfort for up to 1 day following participation. Participants might experience slight skin irritation due to adhesives and gels used during testing.

WILL I BENEFIT IF I TAKE PART?

There is no direct personal benefit from your participation in the study. Indirectly, the study will allow for the identification of internal mechanisms associated with improved performance during running. This fundamental information may be utilized by athletes and footwear companies in order to optimize the mechanical properties of the footwear to their musculoskeletal system.

DO I HAVE TO PARTICIPATE?

Participation in the study is voluntary and you may withdraw from the study at any time for any reason. Your continued participation should be as informed as your initial consent so you should feel free to ask for clarification or new information throughout your participation.

WILL I BE PAID FOR PARTICIPATING, OR DO I HAVE TO PAY FOR ANYTHING?

You will not be paid for your participation in the study. You will be reimbursed for the cost of parking at a rate of \$12 per visit.

WILL MY RECORDS BE KEPT PRIVATE?

All information collected in this study will remain absolutely confidential. Only those directly involved in the study will have access to the information. Any report finding will be published in a manner that no way identifies your participation in the study. You may request the removal of your data from the study at any point prior to the beginning of data analysis.

IF I SUFFER A RESEARCH-RELATED INJURY, WILL I BE COMPENSATED?

In the event that you suffer injury as a result of participating in this research, no compensation will be provided to you by the University of Calgary or the Researchers. You still have all your legal rights. Nothing said in this consent form alters your right to seek damages.

SIGNATURES

Your signature on this form indicates that you have understood to your satisfaction the information regarding your participation in the research project and agree to participate as a participant. In no way does this waive your legal rights nor release the investigators or involved

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institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time. If you have further questions concerning matters related to this research, please contact:

Dr. Darren Stefanyshyn (403) 220-8637

darren.stefanyshyn@ucalgary.ca

Or

Dr. Bill Wannop (403) 220-7003

b.wannop@ucalgary.ca

If you have any questions concerning your rights as a possible participant in this research, please contact the Chair, Conjoint Health Research Ethics Board, University of Calgary at 403-220-7990.

Participant's Name

Signature and Date

Investigator/Delegate's Name

Signature and Date

Witness' Name

Signature and Date

The University of Calgary Conjoint Health Research Ethics Board has approved this research study.

A signed copy of this consent form has been given to you to keep for your records and reference.