The Influence of Footwear Longitudinal Bending Stiffness on Running Economy and Biomechanics in Older Runners

Richard Beltran

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THE INFLUENCE OF FOOTWEAR LONGITUDINAL BENDING STIFFNESS ON
RUNNING ECONOMY AND BIOMECHANICS IN OLDER RUNNERS

by

Richard Tiongson Beltran

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Abstract

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Major Professor: Dr. Max R. Paquette

Footwear longitudinal bending stiffness manipulated with carbon fiber inserts has shown conflicting findings on running economy in young runners. Given the lower ankle torque and power observed in older compared to young runners, more footwear bending stiffness could benefit running economy of older runners as it is expected to attenuate age-related changes in biomechanical function related to economy. The purpose of this study was to assess the effect of running footwear longitudinal bending stiffness manipulated using carbon fiber inserts on running economy and biomechanics of older runners. Nine runners over 60 years (four women) completed five-minute running bouts at their preferred running pace in three footwear conditions: low bending stiffness (4.4 ± 1.8 N·m⁻¹, LS), moderate bending stiffness (5.7 ± 1.7 N·m⁻¹, MS), and high bending stiffness (6.4 ± 1.6 N·m⁻¹, HS). Testing order was randomized and a mirror testing design was used (e.g., LS, MS, HS, HS, MS, LS). Expired gases, lower limb kinematics, and ground reaction forces were collected simultaneously. Lower limb joint kinetics, running economy (VO₂), leg stiffness, and spatio-temporal variables were computed. Running economy was not different among the three different stiffness conditions without adjusting for mass and when adjusting for mass. More shoe stiffness reduced step length, but ankle joint kinetics, propulsive force, and leg stiffness were not different among the three different stiffness conditions. The findings from this study demonstrate that increasing footwear longitudinal bending stiffness using flat carbon fiber inserts does not improve running economy and generally does not alter lower limb joint mechanics of older runners. However, given the current evidence on the influence of footwear bending stiffness and other footwear characteristics on MTP joint mechanics and running economy, future research on this population should consider MTP joint mechanics.
PREFACE

The findings from this thesis will be submitted for publication to the journal *Sports Medicine* and the formatted manuscript for this journal is presented in chapter II. Therefore, references are formatted specifically for this journal.
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<td>BMI</td>
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CHAPTER 1
INTRODUCTION

1.1 Statement of the Problem

Participating in regular physical activity is associated with many different health benefits [1]. One popular form of physical activity is running, as it is accessible to many individuals because it is convenient and inexpensive. The running population increases each year and much of that is attributed to the master runner population increasing due to runners continuing to participate in later stages of their life as well as it being an easy activity for older individuals to take up [2,3]. Running is associated with mental, physiological, as well as musculoskeletal benefits. Many individuals who participate in running at an older age have superior cardiovascular and musculoskeletal health compared to non-active older individuals [4–6]. Therefore, these individuals who are still running may attenuate the age-related declines in cardiovascular and musculoskeletal health.

However, age-related changes in musculotendinous properties influence biomechanical output while running and can alter the metabolic cost of running. Greater metabolic costs may reduce motivation for continued running with age and as a result, limit health benefits of continued running participation. As runners get older, ankle power generation decreases [7] in which limits propulsive capacity during running [7]. Lower propulsive capacity may have implications for increasing metabolic costs and perceived effort [8]. Thus, biomechanists and physiologists aim to identify strategies and interventions to optimize propulsive capacity to ensure lower metabolic costs and perceived efforts of running. Successful reductions in
metabolic costs and perceived effort might help increase motivation and reduce attrition to running participation with older age.

Certain footwear types have been found to reduce metabolic costs via reduced joint work during running, therefore lowering the perceived effort. Specifically, the shoe weight, midsole cushioning and the longitudinal bending stiffness of the shoe and their effects on running-related variables have been studied by researchers to improve metabolic costs [9–12]. Hoogkamer et al found that decreased shoe weight, increase midsole material energy return and high longitudinal bending stiffness in the same pair of shoes potentially improves running economy [13] However, these previous research studies examining the footwear effects on runners has been done on young and healthy runners. Since the population of older runners is increasing and many of the footwear studies are performed on younger runners, more research studies are needed examining the effect of shoe weight, midsole cushioning and longitudinal bending stiffness on older runners. Given the lower ankle power generation and propulsive capacity, footwear with greater longitudinal bending stiffness may be beneficial for minimizing energetic costs through improved propulsive capacity.

1.2 Literature Review

Running is an easy and convenient form of aerobic exercise. Running participation and popularity in the United States has been increasing since 1970’s, except for minor drops in 2017 [2]. While participation in running has generally increased, a substantial increase in older runners has been observed [3]. This increase in running participation may potentially be due to individuals continuing to run until later stages of life or due to individuals starting to run at an older age. Whatever the case may be for why more older individuals are participating in running
events, running provides positive effects on cardiovascular, pulmonary and musculoskeletal function and may help attenuate age-related declines in overall health [1].

1.2.1 Benefits of Running

There are many health benefits associated to running participation and training. Participation in running has been found to increase cardiovascular, pulmonary and musculoskeletal function [1]. Running has been known to reduce the incidence of obesity and is also associated with a lower body mass index (BMI), which is associated with better overall health [14,15]. An increase in cardiovascular, pulmonary and musculoskeletal function as a result of running has been shown to improve short-term and long-term health and delay the age-related declines in overall health [14,15].

*Cardiovascular and Pulmonary Function*

The cardiovascular and pulmonary system provides the body with blood and oxygen via the heart, lungs, veins and arteries. During running, the heart and lungs increase blood flow to compensate for the increased metabolic demands [16]. As exercise intensity increases, cardiac output and stroke volume increase with the help of neural and hormonal regulation during exercise [17]. The increased exercise intensity causes stress on the cardiovascular and pulmonary system, and physiological changes in the body occur allowing the systems to adapt to meet the demands placed on them resulting in increased heart rate (HR).

A long-term health benefit of the cardiovascular system due to running is an increase cardiac output. This increase in cardiac output is caused by an increase in blood volume and hypertrophy of the left ventricle which results in a decrease in blood pressure [18,19]. In addition, cardiorespiratory adaptations due to running have also been observed. Endurance running has been shown to significantly increase maximal oxygen uptake by way of more red blood cells or
better $O_2$ saturation in existing blood cells [18]. Running has been shown to increase the arteriovenous oxygen difference (a-VO$_2$ diff), which is a factor associated with aerobic performance that dictates the capacity of skeletal muscle to extract and consume oxygen from the blood [20]. A greater a-VO$_2$ diff would lower the perceived effort of running as there is more oxygen that is available to be used [20]. In addition to the increased cardiovascular and pulmonary function due to running, there are also musculoskeletal benefits.

**Musculoskeletal Function**

The musculoskeletal system consists of muscles, bones, tendons, and ligaments that work together to provide support, stability, and movement to the body. Therefore, it is important for these tissues to function optimally to sustain and maximize endurance performance. The skeleton has the unique ability to adaptively remodel in response to mechanical loading or lack of loading. Wolff’s law states that the bone of a healthy individual will adapt to the loads that are applied to it [21]. In the presence of loading, bone is either maintained or will remodel itself over time to be able to handle the larger load. In the absence of loading, bone density and mass will decrease [21]. While running, the skeletal system is loaded and with proper rest, the bones of the lower extremity will become more dense and resilient. This ability to handle increased loads may increase endurance performance and decrease the risk of potential injury. Internal and external stresses such as ground reaction forces (GRF) and muscle and tendon tensile forces on bone, as well as biochemical processes such as remodeling agents help the bone adapt to increase loads [22]. When the bones sense mechanical strain, the strains and stresses trigger the bone damaging cycle that include osteoblasts, osteoclasts and osteocytes. Osteocytes are one of the major bone cells that sense and react to the stress applied to the bones [23]. When stress and strains are sense, osteoclasts are in charge of degrading dysfunctional or damaged bone while osteoblasts...
synthesizes new bone. If osteoclast activity is greater than osteoblast activity (i.e., rate of tissue damage is greater than rate of tissue remodeling), there will be overall bone damage and/or injury and if there is greater osteoblast activity, bone becomes stronger. With adequate rest to allow for proper remodeling, the skeletal system will strengthen and be able to withstand more stress.

Muscles and tendons can also adapt when they are placed under the appropriate amount of stress. Davis’ law states that tissue adapts to the amount of stress placed upon it. When stress is applied to tissues, they respond by breaking down and then heal according to the manner in which they were stressed [24,25]. However, if the amount of stress applied is too much, the tissue will breakdown which may cause injuries. With the appropriate amount of stress applied, the muscular system will increase in strength and potentially decrease running related injuries that may occur. Therefore, it is important that a proper amount of stress is applied to the body to maximize performance while decreasing the possibility of injury.

Although running is beneficial for musculoskeletal function, running is also associated with high incidences and rates of injuries. Approximately 19-79% of recreational, competitive and elite long-distance runners will sustain a running related injury (RRI) while training with a majority occurring in the lower extremity [15]. Of the RRI’s, 50% were reported to occur at the knee, while 32% were reported to occur at the Achilles tendon, calf, heel, hamstrings and quadriceps [15,26,27]. Compared to younger runners, older runners were reported to have 49% more RRI’s [28]. In addition to the increased likelihood of injury, older runners are also more likely to experience multiple RRI’s in a year than younger runners [28]. While younger runners experience more knee and lower leg injuries, such as iliotibial band pain and medial tibial stress syndrome [28,29], older runners tend to experience more muscular and tendinous injuries to the
hamstrings, plantarflexors, and Achilles tendon, with the most common RRI being Achilles tendinopathy [28]. So although RRI’s are difficult to avoid considering their multifactorial nature and complexity, proper programming and training can be used to reduce the risks of injuries.

1.2.2 Aging

Aging induces physiological changes on the human body that affect how older adults perform activities of daily living. As aging continues, the changes become more drastic and promote a decline in overall function and health [1].

Cardiovascular and Pulmonary Changes

Resting heart rate and cardiac output are minimally affected by the natural aging process. However, diastolic function changes significantly despite the minimal changes in heart rate and cardiac output [25]. The early diastolic filling rate has been found to progressively slow down after the age of 20, and by 80 years the filling rate is reduced by up to 50% [25]. Therefore, in order to have enough blood supply for the body, older individuals may rely on the Frank Starling law in order to increase cardiac output [30]. The Frank Starling mechanism increases cardiac output in response to an increase in stroke volume of the left ventricle causing a stronger contractile force, therefore providing adequate amounts of blood to the body. However, even with the use of the Frank Starling Mechanism, cardiac output was still 20% less in older individuals when compared to young adults [31].

Healthy aging is also associated with alterations in the cardiovascular system that may cause dysfunction. As aging occurs, left ventricle wall thickness increases, left atrial size increases, and the vascular walls thicken and increase in stiffness which all may potentially lead to atherosclerosis or other cardiovascular diseases [4]. Normal aging is also associated with declines in maximal oxygen uptake (VO$_2$ max) [4]. Studies have shown that a lower VO$_2$ max
has been shown to be related to increased risk in developing chronic health diseases [32]. Older sedentary adults have been found to have a maximal oxygen uptake 19-23% less than younger adults [33]. This may be due to the reduction in arteriovenous oxygen difference (a-VO₂ diff) that occurs in normal aging [20]. The arteriovenous oxygen difference dictates the amount of oxygen extracted from the blood and this process is reduced with age. A reduced arteriovenous oxygen difference plays a large part in decreased running performance. The Fick equation (VO₂ = Q*a-VO₂ diff) represents that the body’s oxygen consumption is equal to the a-VO₂ diff and cardiac output (Q). Therefore, due to the age-related reduction in a-VO₂, oxygen consumption is reduced which can negatively affect performance.

Physical activity has been shown to decrease these cardiovascular age-related changes that occur in the body. As aging occurs, maximal aerobic capacity tends to decrease, and this may put older individuals at risk for chronic health diseases. A previous research study has found that highly trained individuals in their 80s had a smaller decline in VO₂ max over a 20-year period when compared to untrained individuals at the same age [34]. This longitudinal study also confirms previous studies that suggest the aerobic capacity of highly trained runners decreases by about 5-7% per decade after the third decade compared to sedentary individuals whose aerobic capacity decreases by about 10-15% per decade [4–6].

Despite aerobic capacity being reduced with age, running economy has been found to not change as runners get older [35]. Running economy is defined as the rate of oxygen consumption at submaximal running speeds and has been found to be a strong predictor of running performance [36]. A previous research study by Beck et al. (2016) found that aging did not cause submaximal oxygen consumption to deteriorate [35]. Therefore, although completely preventing these age-related changes in the cardiovascular system is not possible, endurance running has
been shown to delay the decline in cardiovascular change. These cardiovascular changes may hinder an older runner to not run as fast and long as they are used to because of these age-related changes. As a result of these cardiovascular changes, decline in the musculoskeletal system also occurs which may affect how an individual functions.

**Musculoskeletal Changes**

Healthy aging causes many structural and functional changes in the skeletal muscle. The most evident musculoskeletal changes that occur due to aging are decrease in skeletal muscle size and strength. The loss of muscle tissue is a natural part of the aging process called sarcopenia. Sarcopenia typically begins around 40 years old and studies have found that by age 80, up to 50% of muscle mass could be lost [37]. Sarcopenia may be caused by inflammatory pathway activation, decrease in mitochondria production and alterations in current mitochondria, the loss of neuromuscular junctions, age-related molecular changes and hormonal changes [36].

A result of sarcopenia is the decline in maximal voluntary contractions and muscle thickness [38]. As aging occurs, muscle fibers are still able to produce and recover from contractions with minimal change, however, the force of the muscle contractions significantly decline with age [38–40]. A previous study compared tendon stiffness and cross-sectional area as well as muscle size and found that older individuals had 17% less tendon stiffness and a 16% larger tendon cross-sectional area than younger individuals [41]. This study also found that the triceps surae muscle size was smaller and the gastrocnemius medialis length was shorter in older individuals [41]. These age-related declines in the human body may affect the biomechanics of an older runner which may increase the likelihood of developing a running-related injury.
1.2.3 Biomechanics in the Master Runner

As runners get older, there are running biomechanics that are potentially altered due to the age-related declines in the body. Some of the common changes seen as runners get older is a decrease in running velocity, step length and an increase in stride frequency which may be attributed to cardiovascular and musculoskeletal changes [42]. As age increases, DeVita et al. (2016) predicted that running velocity to decrease by 0.10 m/s over each decade by using a regression equation [7]. In addition, a previous study has shown that older runners have a 4-6% higher stride frequency than younger runners when running at the same speeds (37). In relation to stride frequency, regression models based on adult runners predicted a 13% reduction in stride length by the sixth decade and a 20% reduction by the eighth decade (10). As a result of increased stride frequency and decreased step length, older runners have been found to have greater knee flexion at footstrike and less ankle, knee and hip excursion when compared to younger runners [7,43].

Master runners have also been found to have less maximum peak propulsive and vertical ground reaction forces than younger runners as a result of a decreased running speed (10). The plantarflexor muscle group plays an important role in propulsion and support during running. A previous research study found that peak propulsion force during running is strongly related to concentric ankle power [43]. Concentric ankle power during running has been found to decrease as age increases and with this decrease in ankle power, it is thought that concentric hip and knee power would increase to compensate for the decreased ankle power, however that does not occur. Knee and hip power is found to stay the same in older runners when ankle power is decreased [43]. This decline in concentric ankle power may contribute to why older runners have a decrease in running performance compared to younger runners as concentric ankle power plays
an important role in propulsion during running [43]. However, it has also been noted that older runners who have a similar weekly training volume as younger runners have similar ankle torque and powers as those younger runners [44]. Therefore, maintaining weekly training volume as runners age is important in reducing the age-related biomechanical changes and may be needed to reduce the possibility of running injuries in older runners. Although continued running for older individuals has been shown to attenuate age-related declines in the body, many older runners quit running because of the lack of improved results as well as perceived effort increasing. Therefore, developing short and long term strategies to combat the age-related reductions in plantarflexor propulsive function may help maintain running performance and reduce perceived effort in older runners.

1.2.4 Footwear and Running Biomechanics

Different Types of Shoes

There have been many studies examining the biomechanical effects of various running shoes. Various factors related to running shoes such as strike pattern, midsole thickness, shoe mass and midsole stiffness have been extensively studied. One shoe feature that researchers have studied is the shoe midsole thickness. There are highly cushioned shoes, minimally cushioned shoes, shoes that simulate barefoot running, and neutrally cushioned shoes. The thought is that footwear with a thicker midsole is able to provide more cushioning and lessen the shock during ground contact and therefore, decrease the loading rates while running [29,45]. A previous study by Law et al. (2018), found that shoes with a midsole thickness greater than 5-mm lead to decreased vertical loading rates compared to shoes with less than 5-mm of thickness [46]. Therefore, choosing the right pair of shoes may enhance an individual’s running experience.
However, the best shoe for a runner may depend on the runner’s biomechanics. A forefoot strike (FFS) runner may need a different pair of shoes compared to a rearfoot strike (RFS) runner. A reason for this is habitually shod runners tend to RFS when running while habitual minimalist shoe or barefoot runners FFS or midfoot strike (MFS) [47]. As a result of this, the impact peak and loading rate that is generated when running differs by foot pattern [47,48]. Based on this previous research, it seems that there may be an interaction between footstrike pattern and footwear. This interaction emphasizes the importance of appropriate footwear and choosing the right shoes based on strike pattern. This has been previously shown in high longitudinal bending stiffness shoes as RFS runners have been found to significantly improve running economy [10,12].

**Longitudinal Bending Stiffness**

The longitudinal bending stiffness is a shoe feature that researchers have been studying in relation to running performance [9,12]. Although studied for several decades, longitudinal bending stiffness shoes have garnered much attention recently due to the new Nike performance shoes. Studies by Stefanshyn et al have paid close attention to the metatarsophalangeal (MTP) joint and how it contributes to energy loss during running [12,49]. A study in particular found that increased bending of the MTP joint caused a loss of energy during running [49]. In another study by these same authors, it was found that when the longitudinal bending stiffness of the shoe was increased and the range of motion of the MTP joint decreased, the amount of energy lost during running was reduced [12]. Therefore, increasing the longitudinal bending stiffness of a shoe may save energy, however, it is still in question whether this energy saved will increase endurance running performance.
In addition to the effect on the MTP joint by high longitudinal bending stiffness shoes, previous studies have shown that ankle, knee and hip joint work is effected as well [10]. Hoogkamer et al found that the high longitudinal bending stiffness shoes caused a smaller peak ankle moment and both the negative and positive work rates at the ankle were lowest compared to the other typical marathon racing shoes [10]. However, there were no significant differences in the knee and hip joint moment, power or work when running in the high longitudinal bending stiffness shoes [10]. In a different study by the same researchers, the high longitudinal bending stiffness shoes lowered the energetic cost of running by about 4% [13]. This reduction in the energetic cost of running may be attributed to the mass, midsole compliance, resilience and longitudinal bending stiffness of the shoe.

Other studies have looked at if longitudinal bending stiffness has an effect on running economy, as running economy has been previously been a strong indicator of running performance (30). A study by Roy and Stefanshyn examined the effect that longitudinal bending stiffness has on running performance and found that an increased longitudinal bending stiffness significantly improved running economy [12]. However, it is important to note that this study described the relationship between running economy and midsole longitudinal bending stiffness as a “U-shaped” curve, suggesting that there may be an optimal longitudinal bending stiffness [12,50,51]. Another study that examined the effect of midsole longitudinal bending stiffness on running economy did not find any significant relationship between the two [9]. However, the study did find that the greater longitudinal bending stiffness induced a longer propulsion time and greater vertical stiffness which may potentially be beneficial for improving running economy [9]. Therefore, longitudinal bending stiffness might improve running economy, however these
studies were performed on young healthy runners and the effects of carbon fiber plates on older runners is still unknown.

1.3 Gaps in the Literature

There is limited research currently out that examine the interaction effect between footwear and age on running economy and joint biomechanics as much of the current literature on the footwear is on young healthy runners. The longitudinal bending stiffness of shoes has been previously studied and considering that an increased longitudinal bending stiffness may be beneficial for running economy, studies are needed to assess how this may affect older runners and their running biomechanics. This is important because as individuals get older, the age-related changes that occur to the body may increase the perceived effort of running. With previous research showing that high longitudinal bending stiffness shoes may improve running economy and attenuate some of the age-related changes that occur, older runners might experience all of the positive health benefits of running.

1.4 Research Question and Hypothesis

Purpose

The purpose of this study was to assess the effect of running footwear longitudinal bending stiffness on 1) running economy, 2) effort, and 3) biomechanics of runners over 60 years.

Research Question

1) Will greater footwear longitudinal bending stiffness improve the running economy of older runners?
2) Will footwear longitudinal bending stiffness change the running biomechanics of older runners?

Hypotheses

1) Greater longitudinal bending stiffness will improve running economy in older runners.

2) Greater longitudinal bending stiffness will increase peak plantarflexor torque, increase peak positive ankle power, produce similar ankle work, and increase leg stiffness with in older runners.

1.5 Implications and Relevance

Findings from this study will provide useful information to older runners. If running economy and biomechanics improves with greater longitudinal bending stiffness, it will provide information to older runners on what footwear may be beneficial for continuing or starting running into older age. Findings from this study may also be useful for footwear manufacturers as it may provide information for developing footwear for older runners.
CHAPTER II

The Influence of Footwear Longitudinal Bending Stiffness on Running Economy and Biomechanics in Older Runners
Richard T. Beltran, Daniel Greenwood, Douglas W. Powell, Max R. Paquette

Manuscript in preparation for Sports Medicine

Introduction

Endurance running participation has been growing and this has been particularly evident for older runners [2,52]. This increase in participation in older runners may contribute to healthy aging as endurance running has been shown to reduce age-related declines in function and cardiovascular health and all-cause mortality [5,6,53]. Adherence to group-based beginner running programs for older runners have been found to be positively correlated with enjoyment, motivation, confidence, satisfaction with progress, and social support [54]. However, with age, higher intensity and longer duration runs require greater perceived effort and become more difficult. The primary reasons for elevated perceived effort at a given running pace are related to lower maximal aerobic capacity, maximal heart rate, and cardiac output in older runners [55,56] and therefore, oxygen consumption (VO\textsubscript{2}) relative to maximal capacity was higher in older compared to young runners [57]. This elevated relative VO\textsubscript{2} is certainly related to natural aging processes but can also be explained by changes in training exposures including reduced training volumes and intensities due to several lifestyle factors (e.g., family, work, etc…) [58].

Further, older adults run with lower peak propulsive and vertical ground reaction forces (GRF) [7] that are likely the result of lower peak plantarflexor torque, peak ankle positive power, and positive ankle work [7,42,59]. These reductions may be due to reduced muscle mass, cross-sectional area, rates of force development, and tendon stiffness of the plantarflexors compared to
young runners [39,41]. These age-related changes in physiological, biomechanical, and morphological characteristics likely contribute to shorter step lengths (higher cadence), and higher rates of perceived exertion and ultimately, slower preferred training pace compared to young runners (8). Since increased perceived effort and physiological demands [34] while running in older runners could reduce overall running participation, strategies to facilitate continued or initiation of running participation by improving their running experience could presumably lead to positive health outcomes for older adults in future decades.

A possible acute strategy to help older adults begin running programs by attenuating these age-related running declines in function was through specific types of footwear. Specifically, footwear with carbon fiber plates to increase the longitudinal bending stiffness of the footwear, thick soles, more compliant and resilient foam (i.e., better energy return), and a curved sole have been found to improve running economy (i.e. rate of oxygen consumption at submaximal speeds) by 4% [10,13]. Compliant and resilient midsole foam improves storage and return of energy which contributes to lower the energetic cost of running [13,60]. However, the previously suggested mechanism of a stiffer lower limb via smaller knee flexion [13,61] is not consistent in the literature [10]. Lower metatarsophalangeal (MTP) dorsiflexion and negative work with small reductions in ankle negative and positive work appear to contribute to these lower energetic costs [10]. This is likely the result of muscles operating at about 25% efficiency (i.e., 1 J of mechanical work requires about 4 J of metabolic work [62]. Since these types of shoes can improve metabolic costs in young runners, it would be expected that the shoes could produce similar improvements in older runners. However, given the multiple shoe construct factors that interact to yield those metabolic improvements, it would be useful to pursue this line of research by isolating individual shoe construct factors.
Greater footwear longitudinal bending stiffness with carbon fiber inserts has been shown to improve running economy by about 1% [12] but others have shown no changes in running economy with greater footwear longitudinal bending stiffness [9,63,64]. These conflicting results may be due to different running speeds and varying footwear longitudinal bending stiffnesses in each study. Dorsiflexion at the MTP joint causes a loss or dissipation of energy during running. Therefore, carbon fiber inserts can reduce MTP dorsiflexion and reduce the amount of energy lost at this joint to reduce the energetic costs of running [12,63]. In addition, increasing longitudinal bending stiffness has been shown to change the moment arms of the lower limb joints, with larger changes occurring at the ankle [65]. The larger moment arm with carbon fiber inserts can increase torque at the ankle [65] which may help decrease the redistribution of distal to proximal joint torque and powers [66] and reduce running economy as the muscle-tendon units around the ankle are more economical for producing force than those around the hip [67]. However, it has also been proposed that more footwear bending stiffness can alter the ratio between the moment arms of the plantarflexors and GRF relative to ankle joint center to slow muscle contractile velocity in young runners [65,68]. This, in turn, could reduce peak concentric plantarflexor torque in mid- to late-stance of running in young runners. Further, despite small to large reductions (i.e., effect sizes ($d$) = 0.23 to 0.90 depending on degree of stiffness), negative and positive work is generally not statistically different with more footwear bending stiffness in young runners [69,70]. Further, this anterior shift in the moment arm can also increase ground contact time which may improve running economy [65]. Short ground contact times induce a high metabolic cost as faster force production demands require recruitment of fast twitch muscle fibers that consume energy faster [71,72]. However, other studies have shown that long contact
times may produce a higher metabolic cost due to slower force development and therefore require longer periods of muscle activation [62].

Lastly, the use of carbon fiber inserts increases vertical stiffness [9] which has been related to improvements in running economy [35,73]. The spring-like storage and return of elastic energy from the leg during stance is important for running economy improvement [8]. Since the leg is characterized as a spring-mass model during running, stiffness plays an important in storing and returning energy to the runner [74]. Since older runners run with lower peak vertical GRF [7], more knee flexion [75], less leg stiffness [35], and less ankle and knee stiffness [75,76] than younger runners, carbon fiber inserts may serve to increase leg stiffness and potentially improve running economy. Further, given the reduced ankle torque and power observed in older compared to young runners [7,35,42], carbon fiber inserts could benefit running economy of older runners as they are expected to attenuate age-related changes in biomechanical function related to economy. Specifically, the increased ankle moment arm may be effective in improving the ankle propulsive function and reduce the distal to proximal shift of muscular demand that occurs with aging due to reduced ankle push-off.

Therefore, the purpose of this study was to assess the effect of running footwear longitudinal bending stiffness manipulated using carbon fiber inserts on running economy and biomechanics of runners over 60 years. We hypothesized that greater footwear longitudinal bending stiffness will improve running economy in older runners. We expected that this improvement in running economy would be concomitant with greater leg stiffness and peak plantarflexor torque and peak negative and positive ankle power, but similar negative and positive ankle work compared to lower footwear bending stiffness in older runners.

Methods
**Participants**

We recruited nine runners (four women; 67±3 years; 69.5±9.6 kg; 1.71±0.1 m) through running clubs, recruitment flyers, and social media. Inclusion criteria consisted of: fitting an EU shoe size 38, 39, or 40 (women), and 42, 43, or 44 (men) (limited by shoe availability), have been running at least 16km per week for the last 6 months, have been running for at least 10 years, run with a rearfoot strike pattern, and can run at least 30 minutes without stopping (to avoid fatigue effects during testing). Participants were included in this study if they had no current lower limb musculoskeletal injuries or pain and had not previously worn footwear with a carbon fiber plates embedded into the shoes. Each participant was provided with verbal and written procedures, potential risks, and benefits of participating this study approved by the Institutional Reviewer Board and were provided verbal and written consent to participate in this study.

**Experimental Procedures**

An 8-camera three-dimensional (3D) motion capture system (240 Hz, Qualysis AB, Sweden) and an instrumented force treadmill was used to simultaneously collect kinematic and GRF data during running trials, respectively. In addition, a metabolic system (TrueOne 2400; ParvoMedics, Murray, Utah) was used to collect expired gases (to calculate running economy) while running. The gases and flow meter for the metabolic system was calibrated prior to each testing session (< 0.4% error). Before the warm-up, neoprene wraps to hold reflective marker clusters were secured to the right shank and thigh, and around the pelvis to make sure the wraps settle onto the participants in order to avoid any tracking marker displacements during experimental trials. Participants then performed a five-minute warm-up on the experimental treadmill at a self-selected speed in their own running footwear. Before experimental testing,
anatomical reflective markers were placed on the right and left iliac crests and greater
trochanters, and on the right femoral epicondyles, malleoli, and head of the first and fifth
metatarsals to define the pelvis and right thigh, leg, and foot. In addition, clusters of tracking
reflective markers mounted non-collinearly on thermoplastic shells were secured and taped to the
neoprene wraps on the pelvis, right thigh, and shank. A thermoplastic shell with three non-
collinear spherical markers were secured on the heel of the right foot. A one-second static
calibration trial was taken to define the segment dimensions, joint centers, local coordinate
systems. Although the same tracking marker clusters were used for both testing conditions, a
different static trial was performed for each testing condition and the anatomical markers were
removed for the running trials. Finally, before the start of experimental testing, participants were
fitted with a rubber facemask (covering the nose and mouth) connected to the metabolic system
via a breathing tube.

Participants then completed the experimental testing protocol on a force instrumented treadmill
(Bertec, USA) in three testing conditions: 1) high stiffness (HS) (i.e., four 1mm thick carbon
fiber inserts), 2) moderate stiffness (MS) (i.e., two 1mm carbon fiber inserts), and 3) low
stiffness (LS) (i.e., without a carbon fiber insert). The conditions were manipulated with a
custom-made carbon fiber inserts (Figure 1A and 1B) placed under the insole of a standard
laboratory shoe (“Run Confort Noir”, Kalenji, Decathlon, France; Figure 2). While wearing the
tracking marker clusters, participants then ran for three to five minutes at their preferred running
speed (2.3 ± 0.15 m·s⁻¹) in each testing condition, separated by a two-minute rest period (i.e., to
change the footwear) to become familiar with the testing conditions (i.e., facemask, footwear)
and to ensure stability of running kinematics [77]. After a two-minute rest period, a static
calibration with all anatomical markers was recorded for the first testing condition. A
randomized and mirrored testing order was used for experimental trials [13]. First, participants completed a three to five-minute running trial followed by a two-minute rest period while changing testing conditions. A static calibration with all anatomical markers was then recorded for the second testing condition. Following the second static calibration, participants performed a three to five-minute running trial in the second testing condition followed by a two-minute rest period to change testing conditions. A static calibration with all anatomical markers was then recorded for the third testing condition. Participants then performed two three to five-minute running trials in the third testing condition, separated by a two-minute rest period. A two-minute rest period was provided, and participants completed another three to five-minute running trial in the second testing condition. Following another two-minute rest, the participant then completed a three to final five-minute running trial in the first testing condition. During the two-minute rest periods and immediately following each run, the participants were asked for their rating of perceived exertion (RPE 1-10), as well as shoe comfort on a scale of 1-5, with five being very comfortable and one being not comfortable at all. The participants were blinded to the testing conditions (i.e., single-blind design) as the carbon fiber inserts were placed below the shoe insole. Kinematic and treadmill force data were collected during the last 15 seconds of the first experimental trials for each testing condition while metabolic data were collected continuously in each experimental trial for each testing condition. Figure 3 summarizes the testing protocol.
Figure 1. A) top view of one insert, and B) sagittal view of a 1mm thick carbon fiber insert.

Figure 2. Kalenji, “Run Confort Noir” running shoe used for all testing.
Figure 3. Summary of the entire testing protocol including rest periods and experimental conditions.

**Longitudinal Bending Stiffness Assessment**

In order to measure the longitudinal bending stiffness of each longitudinal bending stiffness condition, a women’s (EU size 40) and men’s (EU size 42 and 43) shoes were inverted on a table and the proximal portion of the shoe was clamped down between two wooden blocks ensuring a consistent position of the clamp and the wooden block [78]. A fishing hook was then inserted into the distal most part of the outsole, from which fishing line was used to hang 1.0, 2.0, and 3.0 kg masses. With a piece of paper behind the anterior portion of the shoe, the location of the anterior tip of the shoe was marked on the piece of paper without mass and after the masses were secure and hanging from the shoe (Figure 4). The vertical displacement of the anterior portion of the shoe was measured and used to calculate the bending stiffness. Masses were converted to weight (N) and the longitudinal bending stiffness was calculated as the slope of a linear regression fitting the four weights (N) and vertical displacements (m) plotted on a graph. The longitudinal bending stiffness of the LS, MS, and HS conditions were $4.4 \pm 1.8 \text{ N} \cdot \text{m}^{-1}$, $5.7 \pm 1.7 \text{ N} \cdot \text{m}^{-1}$ (+30%), and $6.4 \pm 1.6 \text{ N} \cdot \text{m}^{-1}$ (+45%), respectively. Thus, bending stiffness was ~30% greater in MS and ~45% greater in HS compared to LS, and ~12% greater in HS.
compared to MS. The same researcher conducted the stiffness test for each condition to ensure consistent measurements.

![Figure 4. Set-up of the longitudinal bending stiffness test.](image)

**Data Analyses**

The average VO$_2$ and heart rate from the last minute of each experimental condition was used for analysis. Since VO$_2$ increases by about 1% for each 100 g of mass added to shoes [11], we adjusted VO$_2$ to account for the added mass of the carbon fiber inserts. Inserting two carbon fiber inserts (i.e., MS) added 17.6 g to the shoe and inserting four carbon fiber inserts (i.e., HS) added 35.2 g to the shoe for the men. For the women, inserting two carbon fiber inserts added 14.0 g to the shoe and inserting four carbon fiber inserts added 28.0 g to the shoe. Therefore, for the men we adjusted VO$_2$ by 0.176% and 0.352% and for the women we adjusted VO$_2$ by 0.14% and 0.28% for these conditions, respectively.
Visual3D software (C-Motion, Germantown, MD, USA) was used to process and analyze kinematic and kinetic variables from the running trials. Kinematic data were interpolated using a least-squares fit of a 3rd order polynomial, with a three data point fitting and a maximum gap of 10 frames. Kinematic and ground reaction force data was filtered using a low-pass Butterworth filter with cut-off frequencies of 8 Hz and 40 Hz, respectively. A vertical GRF threshold of 20N was used to define the start and end of the stance phase. A right-hand rule with a Cardan rotational sequence (x-y-z) was used for the 3D angular computations where x represents the medial-lateral axis, y represents the anterior-posterior axis, and z represents the longitudinal axis. The ankle, knee, and hip joint angular kinematic and kinetic variables was expressed in the shank, thigh, and pelvis coordinate systems, respectively. Cadence (steps per minute) was calculated as the number of steps per 15-second trials multiplied by four, while step length (meters) was calculated by dividing running speed (meters per second) by cadence. To confirm the rearfoot strike pattern of all participants, sagittal plane foot contact angle was calculated as the 3D sagittal plane formed between the lab coordinate system and the foot coordinate system at time of initial foot contact. Newtonian inverse dynamics was used to calculate net internal joint moments normalized to body mass (Nm·kg\(^{-1}\)) during the stance phase. Joint powers normalized to body mass (W·kg\(^{-1}\)) was computed as the dot product of joint moments and angular velocities, and joint angular work (J·kg\(^{-1}\)) was computed as the time integral of the joint angular power using the trapezoidal rule using a custom program in MATLAB (MathWorks, Natick, MA, USA). Finally, leg stiffness was calculated as per Farley et al. [79]: \( k_{leg} = \frac{F_{peak}}{\Delta L} \), where \( \Delta L = \Delta y + L_0(1 - \cos\theta) \) and \( \theta = \sin^{-1}\left(\frac{v_t}{2L_0}\right) \) (\( \Delta y \) was the peak vertical displacement of center of mass during stance phase; \( v \) = horizontal velocity; and \( t_c \) = stance time).

**Statistical Analyses**
Data normality was assessed using the Shapiro-Wilk test and confirmed normality was not violated. Repeated measures analysis of variance with testing condition (HS, MS, and LS) as the within-subject factor was used to assess the effects of the carbon-fiber plate inserts on all biomechanical and metabolic dependent variables. Cohen’s $d$ effect sizes was calculated to assess effect magnitudes (i.e., small: $d \leq 0.2$, moderate: $0.2 > d < 0.8$; large: $d \geq 0.8$) [80]. Significance level was set at $p \leq 0.05$.

Results

**Footwear Comfort**

There were no differences in reported comfort among shoe stiffness conditions ($p=0.64$). The average comfort rating for the LS, MS, and HS were 3.6±0.9, 3.8±0.8, and 3.6±1.3 out of 5, respectively.

**Running Economy, Heart Rate, and RPE**

Running economy was not different among the three different shoe conditions without adjusting for mass ($p=0.60$; Table 1, Figure 5a) and when adjusting for mass ($p=0.53$; Figure 5b). 3 runners (~33%) had improved mass adjusted running economy by more than 5% (-7.2 to -9.5%), 5 runners (~56%) had no changes in mass adjusted running economy (-0.6 to +1.3%), and 1 runner (~11%) had worsened mass adjusted running economy 8.8% (Figure 5). Heart rate was not different among the three shoe stiffness conditions ($p=0.570$; Table 1) RPE was also not different among the three shoe stiffness conditions ($p=0.98$; Table 1).
Figure 5. a. Running economy (expressed as oxygen consumption \([\text{VO}_2]\)) while running the low, moderate, and high bending stiffness conditions. b. Running economy (expressed as oxygen consumption \([\text{VO}_2]\)) adjusted for added mass while running the low, moderate, and high bending stiffness conditions.

Table 1. Running economy (expressed oxygen consumption \([\text{VO}_2]\) and rate of perceived effort (RPE; 10-point scale) for Low, Moderate, and High longitudinal bending stiffness conditions (mean ± SD).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economy (mL·kg(^{-1})·min(^{-1}))</td>
<td>24.6±3.7</td>
<td>24.3±3.8</td>
<td>24.6±3.5</td>
<td>0.60</td>
</tr>
<tr>
<td>Economy (Adjusted) (mL·kg(^{-1})·min(^{-1}))</td>
<td>24.6±3.7</td>
<td>24.2±3.7</td>
<td>24.4±3.5</td>
<td>0.53</td>
</tr>
<tr>
<td>Heart Rate (BPM)</td>
<td>135±13</td>
<td>135±14</td>
<td>135±13</td>
<td>0.57</td>
</tr>
<tr>
<td>RPE</td>
<td>2.7±0.9</td>
<td>2.7±1.1</td>
<td>2.7±1.1</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Notes: *different than Low longitudinal bending stiffness. Bold: p-value ≤ 0.05.

Foot Contact Angle, Temporospatial, and GRF Variables

All participants were rearfoot strike runners and their strike pattern was maintained among all stiffness conditions (p=0.19) with sagittal plane foot contact angles of 12.4±1.3°,
12.6±1.3°, and 11.1±0.8° for LS, MS, and HS, respectively. Cadence was different among shoe stiffness conditions (Table 2). Cadence was higher in both MS (p=0.04; d=0.41) and HS (p=0.03; d=0.40) compared to the LS condition, but not different between MS and HS (p=0.89; d=0.21).

Contact time was not different among shoe stiffness conditions (Table 2). Step length was different among shoe stiffness conditions (Table 2). Shorter steps were observed in HS compared to LS (p=0.03; d=0.16) but no differences were observed between MS and LS (p=0.93; d=0.15) or between MS and HS (p=0.87; d=0.14).

Peak vertical GRF was different among shoe stiffness conditions (Table 2, Figure 6a). Peak vertical GRF was larger for MS (p=0.02; d=0.17) and HS (p=0.02; d=0.17) compared to LS (Table 2; Figure 6a). Peak propulsive force was not different among shoe stiffness conditions (Table 2, Figure 6b).
Figure 6. a) Vertical GRF and b) Anterior-Posterior GRF time-series for the Low, Moderate, and High longitudinal bending stiffness conditions. *different than Low longitudinal bending stiffness (p ≤ 0.05).

Table 2. Spatio-temporal and ground reaction force (GRF) variables for Low, Moderate, and High longitudinal bending stiffness conditions (mean ± SD).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadence (steps·min⁻¹)</td>
<td>160±9</td>
<td>165±13*</td>
<td>165±12*</td>
<td>0.027</td>
</tr>
<tr>
<td>Contact Time (seconds)</td>
<td>0.289±0.03</td>
<td>0.300±0.04</td>
<td>0.291±0.04</td>
<td>0.27</td>
</tr>
<tr>
<td>Step Length (meters)</td>
<td>0.75±0.04</td>
<td>0.73±0.06</td>
<td>0.73±0.05*</td>
<td>0.046</td>
</tr>
<tr>
<td>Peak Vertical GRF (BW)</td>
<td>2.05±0.17</td>
<td>2.08±0.19*</td>
<td>2.08±0.18*</td>
<td>0.019</td>
</tr>
<tr>
<td>Peak Propulsive Force (BW)</td>
<td>0.14±0.04</td>
<td>0.15±0.04</td>
<td>0.15±0.04</td>
<td>0.081</td>
</tr>
</tbody>
</table>

Notes: *different than Low longitudinal bending stiffness; Step length: anterior distance between right heel position at time of right foot contact and left heel position at time of left foot contact. Bold: p-value ≤ 0.05.
Joint Biomechanics and Leg Stiffness

Peak plantarflexor torque (Figure 7), peak ankle plantarflexion angular velocity (Figure 7), peak negative and positive ankle power (Figure 8), and negative and positive ankle work, were not different among shoe stiffness conditions (Table 3).

Peak negative knee power (Figure 8) was different among shoe stiffness conditions (Table 3). Peak negative knee power was larger for the MS compared to the LS (p=0.04; \(d=0.49\)) and HS (p=0.03; \(d=46\)) conditions (Table 3). Peak knee extensor torque (Figure 7), peak knee angular velocity (Figure 7), and negative and positive knee work were not different among shoe stiffness conditions (Table 3).

No shoe stiffness main effects were observed for peak hip extensor torque (Figure 7), peak hip angular velocity (Figure 7), peak positive hip power (Figure 8), positive hip work, or negative hip work (Table 3). No shoe stiffness main effect was observed for leg stiffness (Table 3).

Table 3. Peak joint extensor torques (Nm·kg\(^{-1}\)), peak joint angular velocity (°/s), peak joint positive and negative angular power (W·kg\(^{-1}\)), joint negative and positive angular work (J·kg\(^{-1}\)), and leg stiffness (kN/m) variables for Low, Moderate, and High longitudinal bending stiffness conditions (mean ± SD).
<table>
<thead>
<tr>
<th>Variables</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak plantarflexor torque</td>
<td>-2.19±0.43</td>
<td>-2.18±0.44</td>
<td>-2.20±0.41</td>
<td>0.65</td>
</tr>
<tr>
<td>Peak knee extensor torque</td>
<td>1.62±0.24</td>
<td>1.71±0.32</td>
<td>1.64±0.24</td>
<td>0.11</td>
</tr>
<tr>
<td>Peak hip extensor torque</td>
<td>-1.54±0.46</td>
<td>-1.64±0.60</td>
<td>-1.64±0.54</td>
<td>0.50</td>
</tr>
<tr>
<td>Peak ankle plantarflexion velocity</td>
<td>-288.67±21</td>
<td>-279.29±18</td>
<td>-279.51±13</td>
<td>0.40</td>
</tr>
<tr>
<td>Peak knee extension velocity</td>
<td>192.3±12</td>
<td>195.3±12</td>
<td>196.7±14</td>
<td>0.71</td>
</tr>
<tr>
<td>Peak hip extension velocity</td>
<td>-323.34±21</td>
<td>-314.64±22</td>
<td>-318.31±22</td>
<td>0.39</td>
</tr>
<tr>
<td>Peak positive ankle power</td>
<td>4.97±1.52</td>
<td>4.85±1.34</td>
<td>4.92±1.38</td>
<td>0.48</td>
</tr>
<tr>
<td>Peak negative ankle power</td>
<td>-4.94±0.96</td>
<td>-4.99±0.88</td>
<td>-5.19±1.02</td>
<td>0.062</td>
</tr>
<tr>
<td>Peak positive knee power</td>
<td>3.13±0.51</td>
<td>3.39±0.54</td>
<td>3.34±0.79</td>
<td>0.59</td>
</tr>
<tr>
<td>Peak negative knee power</td>
<td>-6.33±1.11</td>
<td>-6.95±1.39</td>
<td>-6.39±1.03</td>
<td>0.039</td>
</tr>
<tr>
<td>Peak positive hip power</td>
<td>0.90±0.79</td>
<td>1.06±0.67</td>
<td>1.05±0.42</td>
<td>0.48</td>
</tr>
<tr>
<td>Peak negative hip power</td>
<td>-1.98±1.12</td>
<td>-2.01±1.53</td>
<td>-1.72±1.07</td>
<td>0.34</td>
</tr>
<tr>
<td>Positive ankle work</td>
<td>1.64±0.23</td>
<td>1.65±0.30</td>
<td>1.66±0.29</td>
<td>0.86</td>
</tr>
<tr>
<td>Negative ankle work</td>
<td>-0.35±0.04</td>
<td>-0.35±0.06</td>
<td>-0.35±0.06</td>
<td>0.93</td>
</tr>
<tr>
<td>Positive knee work</td>
<td>0.46±0.11</td>
<td>0.49±0.12</td>
<td>0.50±0.08</td>
<td>0.53</td>
</tr>
<tr>
<td>Negative knee work</td>
<td>-0.31±0.04</td>
<td>-0.33±0.05</td>
<td>-0.31±0.04</td>
<td>0.087</td>
</tr>
<tr>
<td>Positive hip work</td>
<td>0.34±0.12</td>
<td>0.34±0.15</td>
<td>0.36±0.09</td>
<td>0.82</td>
</tr>
<tr>
<td>Negative hip work</td>
<td>-0.15±0.04</td>
<td>-0.14±0.05</td>
<td>-0.15±0.07</td>
<td>0.97</td>
</tr>
<tr>
<td>Leg stiffness</td>
<td>30.2±4.2</td>
<td>29.1±4.2</td>
<td>29.6±3.5</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Notes: *different than Low longitudinal bending stiffness; ^: different than High longitudinal bending stiffness. Bold: p-value ≤ 0.05.
Figure 7. Sagittal plane joint angular velocity (left), net torque (middle), and angular power (right) at the a) ankle, b) knee, and c) hip while running in the low stiffness condition (black), moderate stiffness condition (grey), and high stiffness condition (black dash). *: different than Low longitudinal bending stiffness; #: different than High longitudinal bending stiffness; p ≤ 0.05.

Discussion

This study investigated the effects of footwear longitudinal bending stiffness on running economy and biomechanics in runners over 60 years. Our hypotheses were mostly rejected as running economy and the majority of ankle joint kinetics were not different among footwear stiffness conditions in older runners. The proposed biomechanical mechanisms for improved running economy due to footwear bending stiffness in young runners include increased MTP joint stiffness, minimized energy loss at the MTP joint (i.e., less negative work), and slower plantarflexor muscle contractile velocity [10,12,65,68,70,81]. The unchanged running economy is not surprising given the similar lower limb joint kinetics among footwear bending stiffness conditions. We expected more peak plantarflexor torque with increasing footwear bending stiffness since the carbon fiber inserts were expected to shift the center of pressure anteriorly and
increase the GRF moment arm relative to the ankle joint due to limited MTP joint dorsiflexion. Peak negative and positive ankle power were also unchanged likely as a result of similar peak plantarflexor torque and angular velocity across stiffness conditions. One explanation for the similar ankle kinetics among bending stiffness conditions may be related to the relative slow testing speed (2.3 ± 0.15 m·s⁻¹) used in the study. Study testing speeds and self-reported running speeds of older runners (60-80 years) commonly range between 2.7–3.5 m·s⁻¹ [76,82,83]. Since peak ankle plantarflexor torque [84,85] and MTP joint stiffness (i.e., contributor to lengthening the GRF moment arm to ankle joint) increases with running speed [50], the slow speeds used in the study, combined with the shorter steps taken with more footwear bending stiffness, may not have produced large enough mechanical demands to elicit changes in ankle kinetics among bending stiffness conditions. It is important to note that, although not meeting the a priori set significance level of 0.05 (p=0.062), peak negative ankle power in the HS condition was ~5% greater compared to both LS (d=0.27) and MS (d=0.22). Given the small sample size used this study and the fact that this is a new line of research within the footwear science literature, these small differences should be investigated in larger cohorts under similar footwear conditions.

The similar running economy among stiffness conditions in old runners is consistent with previous research on the influence of footwear bending stiffness on running economy in young runners [9,64]. This is conflicting with some evidence for a 1% improvement in running economy when increasing footwear longitudinal bending stiffness [12]. Previous research found that increasing footwear bending stiffness with carbon fiber inserts increases peak ankle torque [12]. In addition, it has been reported that footwear bending stiffness alters the ratio between the moment arms of the plantarflexors and GRF relative to the ankle joint center to slow muscle contractile velocity which may reduce plantarflexor torque during running [65,68], however
reduced plantarflexor torque was not found in the present study. Our findings are consistent with other previous research that carbon fiber inserts do not change ankle joint kinetics in young runners [64,69,70]. Some have suggested that optimal longitudinal bending stiffness to improve running economy may be speed dependent ([50] and thus, changes regarding economy and joint kinetics may be due to differences in running speed. In the present study the running speed was set to the preferred speed of participants and averaged 2.3 ± 0.15 m·s⁻¹, while other studies who observed improvements in running economy with greater footwear bending stiffness used average testing speeds between 3.8 m·s⁻¹ and 3.9 m·s⁻¹ ([12,50]. Our testing speed was perhaps too slow, but we intended to assess VO₂ and joint mechanics at a speed that would be relevant for our older runner population.

Furthermore, Oh and Park [81] showed that longitudinal bending stiffness should be dependent on the stiffness of the MTP joint to improve running economy. Range of motion of the first MTP joint is lower in adults over 50 years compared to younger (i.e., 20 years) adults [86]. Thus, the optimal footwear longitudinal bending stiffness may change with age given potentially stiffer MTP joints due to lower MTP range of motion. MTP joint stiffness was not measured in the present study, but the longitudinal bending stiffness of the shoes may not have been suitable for the older runners which may contribute to similar the running economy among the different footwear bending stiffness conditions.

Further, lower MTP joint dorsiflexion and negative work have been proposed to contribute to lower metabolic cost in footwear with stiff midsoles and compliant and resilient foam [10]. However, and in a somewhat conflicting concept than the previous, it has also been suggested that running economy can improve when the longitudinal bending stiffness *does not affect* MTP dorsiflexion (i.e., maintenance of natural motion) which may suggest the need for
optimal footwear bending stiffness among individuals [81]. We did not measure MTP joint kinetics and therefore, cannot confirm that MTP joint kinetics were unchanged among stiffness conditions. However, given that economy and most joint kinetic variables were unchanged with more footwear bending stiffness, we hypothesize that bending stiffness did not affect MTP joint kinetics in these older runners. Finally, since MTP joint stiffness increases with running speed [50], the moderate and high footwear bending stiffness conditions may have been too high given the slow speeds used in the current study.

Previous research has found that more longitudinal bending stiffness induces longer contact times [9,64] but we observed shorter steps and faster cadence despite no changes in contact time with more bending stiffness. The shorter steps may explain the similar peak propulsive forces among stiffness conditions which is consistent with previous studies [9,64]. Further, since older runners tend to run with short steps to begin with [7], as mentioned earlier, the relatively slow running speeds may not require a sufficiently large mechanical demand to necessitate longer steps, regardless of more footwear bending stiffness.

Although footwear bending stiffness did not influence leg stiffness, peak positive knee power, and negative and positive knee work, peak negative knee power was greater in the MS compared to LS and HS conditions. The greater peak negative knee power may be related to the larger peak vertical GRF with more bending stiffness which is consistent with previous findings [69]. The greater vertical GRF increases the mechanical demands on the knee joint which acts to dissipate mechanical energy [87] and may be the result of slightly shorter steps to produce a more vertical leg acceleration (i.e., Fz = m·az) before touchdown in the MS and HS conditions. Further, these findings may suggest a “sweet spot” of footwear bending stiffness on rate of eccentric knee extensor action during the stance phase of running in old runners. However,
unaccustomed eccentric muscle actions can increase delayed onset muscle soreness 24-72 hours following exercise. Given that knee extensor DOMS influences lower limb joint mechanics [88], moderate footwear bending stiffness (~5.7 ± 1.7 N·m⁻¹) may be detrimental to older runners as they begin new running training programs to limit rate of eccentric knee extensor action. Further, we expected greater leg stiffness with more footwear bending stiffness as one of the other proposed mechanisms for improved economy due to greater longitudinal bending stiffness is a stiffer lower limb. A critical component of running economy is the spring-like storage and return of elastic energy from the lower limb [35]. During running, the leg is characterized as a spring-mass model. From initial contact to mid-stance, the elastic tissue of the leg is elongated and stores elastic potential and then from mid-stance to toe off, the elastic potential energy is then converted back to kinetic energy [74]. Thus, greater stiffness may improve running economy because of the storage and return of energy from the leg during stance phase. Due to the commonly reported larger peak knee flexion [75], lower leg stiffness [35], and lower ankle and knee joint stiffness [75] in older compared to young runners, carbon fiber inserts were expected to increase leg stiffness. However, there were no differences in leg stiffness thus, the current findings suggest that leg stiffness may not be influenced by footwear longitudinal bending stiffness in older runners.

The small sample size of 9 participants certainly needs to be taken into consideration when interpreting the findings. However, the influence of footwear bending stiffness on running economy and joint mechanics had never been studied and the population sample is fairly homogenous (e.g., rearfoot strike runners, 10+ years of running experience, evenly distributed gender proportion, similar current running exposure). Thus, the findings from this study provide
an initial understanding of the influence of footwear bending stiffness on economy and lower limb joint mechanics in old runners that contribute to the current footwear science literature.

Conclusion

The findings from this study demonstrate that increasing footwear longitudinal bending stiffness using flat carbon fiber inserts does not improve running economy and generally does not alter lower limb joint mechanics of older runners. However, given the current evidence on the influence of footwear bending stiffness and other footwear characteristics on MTP joint mechanics and running economy, future research on this population should consider MTP joint mechanics. Finally, this was the first to study to assess the influence of footwear longitudinal bending stiff on running economy and lower limb joint mechanics of old runners and the implications of this line of future research may play an important role in helping runners continue to run into old age.
References


Appendix A

Table 1. Running economy (expressed oxygen consumption [VO$_2$] and rate of perceived effort (RPE; 10-point scale) for Low, Moderate, and High longitudinal bending stiffness conditions (mean ± SD).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economy (mL·kg$^{-1}$·min$^{-1}$)</td>
<td>24.6±3.7</td>
<td>24.3±3.8</td>
<td>24.6±3.5</td>
<td>0.60</td>
</tr>
<tr>
<td>Economy (Adjusted) (mL·kg$^{-1}$·min$^{-1}$)</td>
<td>24.6±3.7</td>
<td>24.2±3.7</td>
<td>24.4±3.5</td>
<td>0.53</td>
</tr>
<tr>
<td>Heart Rate (BPM)</td>
<td>135±13</td>
<td>135±14</td>
<td>135±13</td>
<td>0.57</td>
</tr>
<tr>
<td>RPE</td>
<td>2.7±0.9</td>
<td>2.7±1.1</td>
<td>2.7±1.1</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Notes: *different than Low longitudinal bending stiffness. Bold: p-value ≤ 0.05.

Table 2. Spatio-temporal and ground reaction force (GRF) variables for Low, Moderate, and High longitudinal bending stiffness conditions (mean ± SD).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadence (steps·min$^{-1}$)</td>
<td>160±9</td>
<td>165±13$^*$</td>
<td>165±12$^*$</td>
<td>0.027</td>
</tr>
<tr>
<td>Contact Time (seconds)</td>
<td>0.289±0.03</td>
<td>0.300±0.04</td>
<td>0.291±0.04</td>
<td>0.27</td>
</tr>
<tr>
<td>Step Length (meters)</td>
<td>0.75±0.04</td>
<td>0.73±0.06</td>
<td>0.73±0.05$^*$</td>
<td>0.046</td>
</tr>
<tr>
<td>Peak Vertical GRF (BW)</td>
<td>2.05±0.17</td>
<td>2.08±0.19$^*$</td>
<td>2.08±0.18$^*$</td>
<td>0.019</td>
</tr>
<tr>
<td>Peak Propulsive Force (BW)</td>
<td>0.14±0.04</td>
<td>0.15±0.04</td>
<td>0.15±0.04</td>
<td>0.081</td>
</tr>
</tbody>
</table>

Notes: *different than Low longitudinal bending stiffness; Step length: anterior distance between right heel position at time of right foot contact and left heel position at time of left foot contact. Bold: p-value ≤ 0.05.
Table 3. Peak joint extensor torques (Nm·kg⁻¹), peak joint angular velocity (°/s), peak joint positive and negative angular power (W·kg⁻¹), joint negative and positive angular work (J·kg⁻¹), and leg stiffness (kN/m) variables for Low, Moderate, and High longitudinal bending stiffness conditions (mean ± SD).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak plantarflexor torque</td>
<td>-2.19±0.43</td>
<td>-2.18±0.44</td>
<td>-2.20±0.41</td>
<td>0.65</td>
</tr>
<tr>
<td>Peak knee extensor torque</td>
<td>1.62±0.24</td>
<td>1.71±0.32</td>
<td>1.64±0.24</td>
<td>0.11</td>
</tr>
<tr>
<td>Peak hip extensor torque</td>
<td>-1.54±0.46</td>
<td>-1.64±0.60</td>
<td>-1.64±0.54</td>
<td>0.50</td>
</tr>
<tr>
<td>Peak ankle plantarflexion velocity</td>
<td>-288.67±21.2</td>
<td>-279.29±18.7</td>
<td>-279.51±13.9</td>
<td>0.40</td>
</tr>
<tr>
<td>Peak knee extension velocity</td>
<td>192.3±12.8</td>
<td>195.3±12.1</td>
<td>196.7±14.6</td>
<td>0.71</td>
</tr>
<tr>
<td>Peak hip extension velocity</td>
<td>-323.34±21.4</td>
<td>-314.64±22.3</td>
<td>-318.31±22.7</td>
<td>0.39</td>
</tr>
<tr>
<td>Peak positive ankle power</td>
<td>4.97±1.52</td>
<td>4.85±1.34</td>
<td>4.92±1.38</td>
<td>0.48</td>
</tr>
<tr>
<td>Peak negative ankle power</td>
<td>-4.94±0.96</td>
<td>-4.99±0.88</td>
<td>-5.19±1.02</td>
<td>0.062</td>
</tr>
<tr>
<td>Peak positive knee power</td>
<td>3.13±0.51</td>
<td>3.39±0.54</td>
<td>3.34±0.79</td>
<td>0.59</td>
</tr>
<tr>
<td>Peak negative knee power</td>
<td>-6.33±1.11</td>
<td>-6.95±1.39^</td>
<td>-6.39±1.03</td>
<td>0.039</td>
</tr>
<tr>
<td>Peak positive hip power</td>
<td>0.90±0.79</td>
<td>1.06±0.67</td>
<td>1.05±0.42</td>
<td>0.48</td>
</tr>
<tr>
<td>Peak negative hip power</td>
<td>-1.98±1.12</td>
<td>-2.01±1.53</td>
<td>-1.72±1.07</td>
<td>0.34</td>
</tr>
<tr>
<td>Positive ankle work</td>
<td>1.64±0.23</td>
<td>1.65±0.30</td>
<td>1.66±0.29</td>
<td>0.86</td>
</tr>
<tr>
<td>Negative ankle work</td>
<td>-0.35±0.04</td>
<td>-0.35±0.06</td>
<td>-0.35±0.06</td>
<td>0.93</td>
</tr>
<tr>
<td>Positive knee work</td>
<td>0.46±0.11</td>
<td>0.49±0.12</td>
<td>0.50±0.08</td>
<td>0.53</td>
</tr>
<tr>
<td>Negative knee work</td>
<td>-0.31±0.04</td>
<td>-0.33±0.05</td>
<td>-0.31±0.04</td>
<td>0.087</td>
</tr>
<tr>
<td>Positive hip work</td>
<td>0.34±0.12</td>
<td>0.34±0.15</td>
<td>0.36±0.09</td>
<td>0.82</td>
</tr>
<tr>
<td>Negative hip work</td>
<td>-0.15±0.04</td>
<td>-0.14±0.05</td>
<td>-0.15±0.07</td>
<td>0.97</td>
</tr>
<tr>
<td>Leg stiffness</td>
<td>30.2±4.2</td>
<td>29.1±4.2</td>
<td>29.6±3.5</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Notes: *different than Low longitudinal bending stiffness; ^: different than High longitudinal bending stiffness. Bold: p-value ≤ 0.05.
Appendix B

Figure 1. A) top view of one insert, and B) sagittal view of a 1mm thick carbon fiber insert.

Figure 2. Kalenji, “Run Confort Noir” running shoe used for all testing.
Figure 3. Summary of the entire testing protocol including rest periods and experimental conditions.

Figure 4. Set-up for the footwear longitudinal bending stiffness test.
Figure 5. a. Running economy (expressed as oxygen consumption [VO2]) while running the low, moderate, and high bending stiffness conditions. b. Running economy (expressed as oxygen consumption [VO2]) adjusted for added mass while running the low, moderate, and high bending stiffness conditions.
Figure 6. a) Vertical GRF and b) Anterior-Posterior GRF time-series for the Low, Moderate, and High longitudinal bending stiffness conditions. *different than Low longitudinal bending stiffness ($p \leq 0.05$)
Figure 7. Sagittal plane joint angular velocity (left), net torque (middle), and angular power (right) at the a) ankle, b) knee, and c) hip while running in the low stiffness condition (black), moderate stiffness condition (grey), and high stiffness condition (black dash). *: different than Low longitudinal bending stiffness; ^: different than High longitudinal bending stiffness; p ≤ 0.05.
Appendix C
Informed Consent for Research Participation

<table>
<thead>
<tr>
<th>Title</th>
<th>The Influence of Footwear Longitudinal Bending Stiffness on Running Economy, Effort, and Biomechanics in Older Runners</th>
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</thead>
<tbody>
<tr>
<td>Researcher(s)</td>
<td>Max R. Paquette, University of Memphis  Richard Beltran</td>
</tr>
<tr>
<td>Researchers Contact Information</td>
<td>865-310-7820, <a href="mailto:mrpqette@memphis.edu">mrpqette@memphis.edu</a></td>
</tr>
</tbody>
</table>

You are being asked to participate in a research study. The box below highlights key information for you to consider when deciding if you want to participate. More detailed information is provided below the box. Please ask the researcher(s) any questions about the study before you make your decision. If you volunteer, you will be one of about 14 people to do so.

<table>
<thead>
<tr>
<th>Key Information for You to Consider</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voluntary Consent:</strong> You are being asked to volunteer for a research study. It is up to you whether you choose to participate or not. There will be no penalty or loss of benefit to which you are otherwise entitled if you choose not to participate or discontinue participation.</td>
</tr>
<tr>
<td><strong>Purpose:</strong> The purpose of this research is to assess the effects of footwear longitudinal bending stiffness on running economy, effort, and biomechanics on runners over 60 years.</td>
</tr>
<tr>
<td><strong>Duration:</strong> It is expected that your total participation during the testing session will last 75-90 minutes.</td>
</tr>
<tr>
<td><strong>Procedures and Activities:</strong> You will be asked to complete six treadmill running bouts of 5 minutes each at a preferred pace with 2min rest breaks between each bout. For each bout, we will have you run in different shoes that we will provide. During the running bouts, you will wear a mask over your mouth and nose to measure the air that you breathe and reflective spheres will be placed on your legs to measure how you move.</td>
</tr>
<tr>
<td><strong>Risk:</strong> Some of the foreseeable risk or discomforts of your participation include soreness from the running bouts in different footwear and potential trips over laboratory equipment. Laboratory staff will be nearby at all times to minimize risks of trips.</td>
</tr>
<tr>
<td><strong>Benefits:</strong> Some of the benefits that may be expected include a better understanding of how footwear longitudinal bending stiffness can affect running performance and biomechanics in runners over 60 years. These findings could also help improve the running experience for runners over 60 years.</td>
</tr>
<tr>
<td><strong>Alternatives:</strong> If you do not want to be in the study, there are no other choices except not to take part in the study.</td>
</tr>
</tbody>
</table>

Who is conducting this research?
Dr. Max R. Paquette of the University of Memphis, College of Health Studies is in charge of the study. There may be other research team members assisting during the study. Members of the research team have no conflicts of interest.

How long will I be in this research?

The research procedures will be conducted in the Musculoskeletal Analysis laboratory (Fieldhouse 171) at The University of Memphis. You will need to come to the Elma Roane Field House, Room 171 for a single testing session that will last approximately 75-90 minutes.

What happens if I agree to participate in this Research?

If you agree to participate, testing will take place at the University of Memphis Musculoskeletal Analysis Lab (Fieldhouse 171). During the laboratory visit you will be informed of all procedures, potential risks, and benefits associated with the study through both verbal and written form. Before testing, you will fill out surveys to make sure you physically able to participate in the study and to provide information regarding your training history.

During the testing session, your mass and height will be measured. Before testing begins, you will complete a five minute warm up at a self-selected pace in your own footwear. Reflective markers (12.5mm plastic spheres covered in reflective tape) will be placed on specific anatomical locations to track lower limb movements during running. The information collected with the motion capture system does not produce video images of you. Instead, it provides positional data (i.e., numbers relative to an origin) of each marker during movement tasks. Therefore, you cannot be identified from this data.

A metabolic system will also be used to collect metabolic data during the treadmill run. The data (gas exchanges: oxygen and carbon dioxide) will be collected with a rubber mask secured over the nose and mouth before the start of the run while you stand on the treadmill. During the treadmill runs, inspired and expired gases will be collected to measure your metabolic cost during running in different footwear conditions.

Following marker placement, a static calibration with all anatomical markers will be recorded for the first testing condition. A randomized and mirrored testing order will be used for the experimental trials. First, you will complete a five-minute running trial followed by a two-minute rest period. During this rest period, you will immediately be asked your rated perceived exertion (i.e. fatigue level) using the Borg Scale of Perceived Exertion, change testing conditions, and fill out a footwear questionnaire about how you think the shoes affected your running performance. A static calibration with all anatomical markers will then be recorded for the second testing condition. Following the second static calibration, you will perform a five-minute running trial in the second testing condition followed by a two-minute rest period to change testing conditions. Again, during this rest period, you will immediately be asked for your rated perceived exertion, change testing conditions, and then fill out a footwear questionnaire about how you think the shoes affected their running performance. A static calibration with all anatomical markers will again be recorded for the third testing condition. You will then perform a five-minute running trials in the third testing condition with a two-minute rest period and again be asked your rated perceived exertion and complete the same questionnaire during the two-minute rest period.
Following this rest period you will then run again for five-minutes in the third testing condition followed by another rest period. After the two-minute rest period, you will complete another five-minute running trial in the second testing condition. Following another two-minute rest, you will then complete a final five-minute running trial in the first testing condition. During the testing session, you will wear a rubber mask over your nose and mouth to measure your breathing. Following each run, the rubber mask will be removed and you will step off the treadmill.

What happens to the information collected for this research?

Information collected for this research will be used to publish scientific articles, reports, conference abstracts and presentations. Your name will not be used in any published reports, conference presentation, etc. We may publish/present the results of this research. However, we will keep your name and other identifying information confidential.

How will my privacy and data confidentiality be protected?

We promise to protect your privacy and security of your personal information as best we can. Although you need to know about some limits to this promise. Measures we will take include:

Files will be kept in a locked file cabinet at which the research team will be the only ones to be able to access it. Any information that gets transferred electronically will be stored on a computer with passcode entry that only the research team will know.

Individuals and organization that monitor this research may be permitted access to inspect the research records. This monitoring may include access to your private information and (include any other records). These individual and organization include:

• Institutional Review Board

What are the risks if I participate in this research?

The potential risks and discomforts that may be experienced are minimal. You may experience soreness from the treadmill run while wearing the medium and high stiffness shoes considering your minimal experience in these footwear. Considering the sub-maximal effort involved and your running experience, it is unexpected that you will experience any soreness following the running tests. If you cannot complete the run due to discomfort in these shoes, the run will be terminated early to avoid pain or injury. There is also a chance that you may trip on laboratory equipment such as the treadmill. A research staff member will be nearby at all times to prevent trips or falls in the laboratory setting.

What are the benefits of participating in this research?

There is no guarantee that you will get any benefit from taking part in this study. However, the results from this study will allow us to further understand how footwear longitudinal bending stiffness can influence running economy, effort, and biomechanics in older runners.

What other choices do I have beside participating in this research?
If you do not want to be in the study, there are no other choices except not to take part in the study.

What if I want to stop participating in this research?

It is up to you to decide whether you want to volunteer for this study. It is also ok to decide to end your participation at any time. There is no penalty or loss of benefits to which you are otherwise entitled if you decided to withdraw your participation. Your decision about participating will not affect your relationship with the researcher(s) or the University of Memphis.

Will it cost me money to take part in this research?

There are no costs associated with participation in this research study.

What if I am injured due to participating in this research?

If you believe you are hurt or if you get sick because of something that is due to the study, you should call Dr. Max Paquette 865-310-7820 immediately. In case of illness or injury during participation in the study, you may reach Dr. Paquette on his mobile phone at 865-310-7820.

If any abnormal signs or symptoms are present during your participation, testing will be terminated and you will receive attention, following the Adverse Events plan of the Human Performance Laboratories. Otherwise, no treatment will be provided.

It is important for you to understand that the University of Memphis does not have funds set aside to pay for the cost of any care or treatment that might be necessary because you get hurt or sick while taking part in this study. Also, the University of Memphis will not pay for any wages you may lose if you are harmed by this study.

Medical costs that result from research related harm cannot be included as regular medical costs. Therefore, the medical costs related to your care and treatment because of research related harm will be your responsibility.

A co-payment/deductible from you may be required by your insurer or Medicare/Medicaid even if your insurer or Medicare/Medicaid has agreed to pay the costs. The amount of this co-payment/deductible may be substantial.

You do not give up your legal rights by signing this form.

Will I receive any compensation for participating in this research?

You will not receive any financial compensation for the study.

Who can answer my question about this research?

Before you decide to volunteer for this study, please ask any questions that might come to mind. Later, if you have questions, suggestions, concerns, or complaints about the study, you can contact the investigator, Dr. Max R. Paquette at 865-310-7820. If you have any questions about your rights as a volunteer in this research, contact the Institutional Review Board staff at the
University of Memphis at 901-678-2705 or email irb@memphis.edu. We will give you a signed copy of this consent to take with you.

STATEMENT OF CONSENT

I have had the opportunity to consider the information in this document. I have asked any questions needed for me to decide about my participation. I understand that I can ask additional questions through the study.

By signing below, I volunteer to participate in this research. I understand that I am not waiving any legal rights. I have been given a copy of this consent document. I understand that if my ability to consent for myself changes, my legal representative or I may be asked to consent again prior to my continued participation.

_________________________  ____________________________  ________
Name of Adult Participant  Signature of Adult Participant  Date

Researcher Signature (To be completed at the time of Informed Consent)

I have explained the research to the participant and answered all of his/her questions. I believe that he/she understand the information described in this consent and freely consent to participate.

_________________________  ____________________________  ________
Name of Research Team Member  Signature of Research Team Member  Date
Appendix D: Training Survey

PARTICIPANT CHARACTERISTICS AND TRAINING HISTORY

1. Participant ID: __________________

2. Height: __________________

3. Weight: ________________

4. Date of Birth: ________________

5. How many years have you been running? ________________

6. What has been your average weekly running mileage since you started running? ________________

7. What has been your average weekly running mileage the last 2 years? ________________

8. What is the typical run distance you complete each week? ________________

9. What is your average running pace on an ‘easy’ run? ________________

10. What shoe(s) (brand and model) do you most commonly wear to run?

    Shoe 1: Brand: _____________ Model: ________________

    Shoe 2: Brand: _____________ Model: ________________

    Shoe 3: Brand: _____________ Model: ________________

11. Do you ever wear carbon-fiber plate shoes for running?

    Circle: Yes    No

    If yes, please provide some details:

    ____________________________________________________________________
Appendix E: Footwear Survey

Participant ID: __________

A. SHOE 1 (Condition _____)
1. How comfortable were these shoes while you were running?
   Likert scale 1-5 (not at all to very much so)
   Not at all            Very much So
   1                   2                   3                   4                 5

2. If the shoe changed how you run, can you describe how this shoe changed how you run?

B. SHOE 2 (Condition _____)
1. How comfortable were these shoes while you were running?
   Likert scale 1-5 (not at all to very much so)
   Not at all            Very much So
   1                   2                   3                   4                 5

2. If the shoe changed how you run, can you describe how this shoe changed how you run?

C. SHOE 3 (Condition _____)
1. How comfortable were these shoes while you were running?
   Likert scale 1-5 (not at all to very much so)
   Not at all            Very much So
   1                   2                   3                   4                 5

2. If the shoe changed how you run, can you describe how this shoe changed how you run?
### Appendix F: RPE Scale

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<th>Descriptor</th>
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<tr>
<td>9</td>
<td>.</td>
</tr>
<tr>
<td>8</td>
<td>.</td>
</tr>
<tr>
<td>7</td>
<td>Very Hard</td>
</tr>
<tr>
<td>6</td>
<td>.</td>
</tr>
<tr>
<td>5</td>
<td>Hard</td>
</tr>
<tr>
<td>4</td>
<td>Somewhat Hard</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
</tr>
<tr>
<td>2</td>
<td>Easy</td>
</tr>
<tr>
<td>1</td>
<td>Very, Very Easy</td>
</tr>
<tr>
<td>0</td>
<td>Rest</td>
</tr>
</tbody>
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Appendix G: IRB Approval

Date: 11-30-2020

IRB #: PRO-FY2021-104

Title: The Influence of Footwear Longitudinal Bending Stiffness on Running Economy and Biomechanics on Older Runners

Creation Date: 11-20-2019 End Date:

Status: Approved

Principal Investigator: Maxime Paquette

Review Board: University of Memphis Full Board

Sponsor:

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Key Study Contacts

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<th>Contact</th>
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<tbody>
<tr>
<td>Maxime Paquette</td>
<td><a href="mailto:mrpqette@memphis.edu">mrpqette@memphis.edu</a></td>
</tr>
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<td>Role Principal Investigator</td>
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<tr>
<td>Maxime Paquette</td>
<td><a href="mailto:mrpqette@memphis.edu">mrpqette@memphis.edu</a></td>
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<td>Role Primary Contact</td>
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</tr>
</tbody>
</table>