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Ankle kinetics and plantarflexor morphology in older runners with different lifetime running exposures

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ANKLE KINETICS AND PLANTARFLEXOR MORPHOLOGY IN OLDER RUNNERS WITH DIFFERENT LIFETIME RUNNING EXPOSURES

By

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ABSTRACT

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Aging is associated with a decline in physical function, cardiovascular health and quality of life. Running promotes better cardiovascular health and has positive effects on the musculoskeletal system in older adults. However, older adults have lower ankle moments and positive powers during running, and exhibit changes in plantarflexor morphology than young adults. These age-related changes contribute to slower running speeds and reduced movement intensity that could influence cardiovascular health. Since older runners who run as much as younger runners exhibit youthful ankle mechanical outputs, running exposure may preserve the locomotor factors that mediate movement speed. The purpose of this study was to compare ankle mechanical output during running and plantarflexor morphological characteristics between older runners who have low or high lifetime running exposure. Twelve older runners with low lifetime running exposure and eight older runners with high lifetime running exposure performed over-ground running trials at 2.7m/s (±5%) while kinematic and ground reaction force (GRF) data were collected. Joint moments and powers were computed using kinematic and GRF data. Right medial gastrocnemius morphological characteristics were assessed using ultrasonography at rest and during isometric contractions. Ankle moments and powers, and plantarflexor morphology were compared between groups using independent t-tests and Cohen's *d* effect sizes. Older runners with different lifetime running exposures ran with similar ankle mechanical output (i.e. no effect of running exposure) (p>0.05). However, older runners with high lifetime exposure ran with greater hip concentric

power (p<0.01, d=1.16), despite similar hip extension torques (p<0.05). Plantarflexor morphological characteristics were similar between lifetime running exposure groups. The findings from this study demonstrate that lifetime running exposure does not influence ankle mechanical output or plantarflexor morphology in older runners but that high lifetime running exposure may lead to greater concentric hip joint involvement during running.

PREFACE

The findings from this thesis will be submitted for publication to the *Scandinavian Journal of Medicine & Science in Sports* and the formatted manuscript for this journal is presented in chapter II. Therefore, references are formatted specifically for this journal.

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ABBREVIATIONS

3D	Three-dimensional
Θ	Pennation angle
FL	Fascicle Length
ΔFL	Change in fascicle length between resting and contracted conditions
AHIMS	Arch height index measuring system
AHI	Arch height index
ATr	Achilles tendon moment arm
a-vO_2 diff	Arteriovenous oxygen differences
BMI	Body mass index
FAOS	Foot and ankle outcome score survey
GM	Medial Gastrocnemius
GRF	Ground Reaction Force
HRE	High lifetime running exposure
LRE	Low lifetime running exposure
MT	Muscle Thickness (mm)
MTU	Muscle Tendon Unit
MU	Motor units
PFC	Plantarflexor complex
Rr	Resistance moment arm
RRI	running related injuries
PFforce	Plantarflexor force
maxHR	Maximum heart rate
VO_2max	Maximal oxygen consumption

CHAPTER I
INTRODUCTION

1.1 Statement of the Problem

It is well documented that physical activity is associated with positive health benefits (Beck et al., 2016; Galloway and Jokl, 2000; Lazarus and Harridge, 2017; Ortega et al., 2014). More specifically, running has been associated with reductions in cardiovascular mortality (Lee et al., 2014), increased muscle endurance (Coggan et al., 1992), lower body mass index (BMI) (P. T. Williams, 2013), and improved overall fitness and physical performance (Tanaka and Seals, 2008). Running is a common form of physical activity that is readily available and economical. However, running-related injuries (RRI) are common in long distance runners (Fields, 2011), and older individuals are more likely to suffer RRIs compared to young runners (Matheson et al., 1989; McKean et al., 2006). Considering, the increased number of older runners finishing competitive races, the higher number of injuries in older compared to younger runners is likely related to loss of muscle mass (Lexell and Downham, 1992; Melton et al., 2000), accompanied by alterations in muscle architecture (Narici et al., 2003) predominantly in lower body skeletal muscles occurring after the 5^{th} decade (Janssen et al., 2000). Normal aging is characterized by reduced muscle mass that may result in less ankle but more hip angular power during the late stance of walking, as well as reduced step length (DeVita and Hortobagyi, 2000a; JudgeRoy et al., 1996). During running, this distal-to-proximal redistribution of joint kinetics is not observed; however, older runners tend to run with lower propulsive ground reaction forces, peak ankle moments and ankle angular powers (DeVita et al., 2016). These kinetic changes result in slower preferred and maximal running speeds (Korhonen et al., 2009) compared to younger runners. Since the magnitude of ankle joint powers and horizontal propulsive forces are strong predictors

of running velocity (Rumpf et al., 2015), mitigating the deterioration of the musculoskeletal system (Lexell et al., 1988; Lexell and Downham, 1992; Lexell, 1997) is important in preserving ankle kinetic parameters, which may perpetuate running speed (Weyand et al., 2000).

Declines in ankle kinetics are related to ankle injury predisposition (Kulmala et al., 2014; Wilkerson et al., 1997) . Considering the large number of older individuals participating in road races (Fields, 2011) and the increased injury risk associated with aging (Nielsen et al., 2013), RRI may result in reduced training, which is needed to mitigate age-related declines in physiological determinants of aerobic performance (Fuchi et al., 1989; Tanaka and Seals, 2008), and the preservation muscle cross-sectional area (Tarpenning et al., 2004). Further, runners between the ages of 13 and 75 with less than three years of running experience are more likely to suffer RRI than individuals with three of more years of experience (Macera et al., 1989). Since, older runners (i.e., 45 to 65 years of age) are more likely to get injured than younger runners (i.e., 18 to 30 years of age) (Nielsen et al., 2013), and less experienced runners are more likely to suffer RRI per 1000 hours of running more than experienced runners (Videbaek et al., 2015). Older runners with less running experience may get injured more frequently than experienced older runners. Lower injury rates lead to greater levels of experience as healthier individuals continue to train, while injury-prone individuals may halt their running participation due to the injury (Macera, 1992; Marti et al., 1988; Seals et al., 2016). Therefore, understanding how running training alters morphology (Narici et al., 2003; Tarpenning et al., 2004) and lower limb biomechanics (Bus, 2003; DeVita et al., 2016; Kulmala et al., 2014) appears to be important for injury prevention (Neely, 1998) and preserving overall cardiovascular health (Tanaka and Seals, 2008) .

Recent evidence suggests that when preferred running pace and average weekly running mileage are similar between young and middle-aged runners, ankle kinetics are not different between groups (Paquette and DeVita, 2018). Older individuals sustain ankle power ($W \cdot kg^{-1}$) by increasing angular velocity to meet the mechanical requirements of running regardless of reductions in ankle internal moments (~10.5%), (Paquette and DeVita, 2018). The authors postulated that faster running paces and more weekly running mileage may have preserving effects on ankle joint kinetics in middle-aged runners. This preservation likely results from the adaptability of tendon and muscle to external loads (Reeves et al., 2002;Reeves et al., 2003;Reeves et al., 2004;Stenroth et al., 2016) which leads to maintenance of muscle strength (Tarpenning et al., 2004) and plantarflexor activation during push-off (Beijersbergen et al., 2017) to ultimately attenuate age-related changes in determinants of endurance performance (Lazarus and Harridge, 2017; Lepers and Stapley, 2016; Tanaka and Seals, 2008). However, rdunning experience (i.e., lifetime running mileage) does not appear to influence running mechanics in individuals between the ages of 15-54 years with an average of eight years of running experience, when accounting for differences in self-selected running (Agresta et al., 2017). To date, the influence of lifetime running experience in middle-aged and older runners is not well understood. Importantly, the decline in endurance exercise performance and its physiological determinants such as maximal aerobic capacity may be mediated largely in part by a reduction in the absolute intensity and total volume of training (Tanaka and Seals, 2008). Thus, an increase in running exposure may lead to reduced losses of ankle function (Paquette and DeVita, 2018), morphology (Karamanidis and Arampatzis, 2006; Stenroth et al., 2016), and cardiovascular determinants of performance (Lepers and Stapley, 2016; Tanaka and Seals, 2008). A better understanding of the influence of greater lifetime training exposure on joint biomechanics and

muscle function in middle-aged runners, may provide more mechanistic explanations for the influence of training exposure on gait function. Improved gait function would allow adults to maintain more youthful movement intensities during exercise which may preserve cardiovascular and musculoskeletal health to ensure healthier aging and better quality of life.

1.2 **Literature Review**

1.2.1 Aging

Training/detraining adaptations may occur at any age. Accordingly, any changes attributed to aging may be influenced by the specific nature of typical physical activity. Typical nutritional intake may also modify structural and functional characteristics of individuals at any age. That being said, natural aging is associated with several physiological and structural changes that influence health outcomes in humans. The first section of this literature review addresses age-related factors related to 1) cardiovascular health, 2) neuromuscular health, 3) musculoskeletal health, and 4) the influence of exercise on aging. This section aims to review contributing factors to the inevitable decrements in overall function, and performance accompanying aging.

Cardiovascular Health

Normal aging is associated with a decline in cardiac output and maximal oxygen consumption (VO_2max), with proportional reductions in maximum heart rate (maxHR) (Tanaka and Seals, 2008). Related, changes in vascular stiffness may facilitate several structural (i.e., myocyte loss and hypertrophy) and functional (i.e., decline in maximal aerobic capacity) changes in the cardiovascular system with advancing age (Heckman and McKelvie, 2008). Although it is difficult to pinpoint the primary mechanism associated with reduced aerobic performance with

aging (Leyk et al., 2007) , it has been reported that maxHR declines with age at a rate of 0.7 beats/min every year for healthy individuals between the ages of 20 and 90 years of age, independent of training status (Tanaka et al., 2001). Moreover, a reduction in arteriovenous oxygen differences (a-vO_2 diff) is a peripheral factor associated with age-related reduction in aerobic performance which reflects a reduced capacity of skeletal muscle to extract and consume oxygen from the blood (Carrick-Ranson et al., 2013). Of course, changes in cardiovascular health only partially contribute to the age-related declines in overall function and quality of life. Deterioration of neuromuscular function with aging can also negatively affect proper motor output during human movement.

Neuromuscular Health

Muscle atrophy with aging (i.e., sarcopenia) is a phenomenon beginning around 25 years of age that continues with chronological age (Lexell et al., 1988). This process accelerates around the 6th decade and by the 8th decade muscle mass reaches a value approximating 60% that of the 2nd decade (Lexell et al., 1988; M. V. Narici and Maganaris, 2006) . This is aggravated by gradual loss in motor units (MU), and alterations to neuromuscular junction morphology (Lynch, 2010), resulting in a decline in muscle strength (Lynch, 2010; M. V. Narici and Maganaris, 2007; Vandervoort, 2002). The neuromuscular junction provides the primary link between motor neurons and muscle fibers, making it essential for neuromotor control and functional performance of skeletal muscles (Lynch, 2010). Rodent studies suggest muscle fibers reduce in size with aging (Balice-Gordon et al., 1990; Li et al., 2011) which may be the result of disuse, and age-related remodeling of both pre- and postsynaptic components (Lexell, 1997; Lyons and Slater, 1991). Similarly, in aging humans, accelerated reduction in cross-sectional area (Narici et al., 2003), a reduction in functioning motor units, loss of motor neurons in spinal cord and loss of

myelinated ventral root fibers (Lexell, 1997; Porter et al., 1995). Like disuse-related atrophy (Wall et al., 2013), sarcopenia is primarily due to a decrease in fiber size but not number (Narici and Maffulli, 2010). Narici et al. (2003) reported that anatomical cross-sectional area (ACSA) (i.e. cross-sectional areal perpendicular to muscle belly or longitudinal axis of muscle) and volume of medial gastrocnemius are approximately 19% and 25% smaller in older (i.e. 70-80 years) compared to younger adults (i.e. 27-42 years). This reduction in muscle size explains the smaller ACSA and physiological cross-sectional area (PCSA) in older compared to younger adults (Narici, 1999; Narici et al., 2003). Considering that PCSA is the area of a muscle cross-section perpendicular to the fibers, the force developed by that muscle is dependent on the proportion of sarcomeres in a parallel arrangement (Narici, 1999). Thus, the small ACSA and PCSA leads to lower voluntary muscle contraction strength with age and these declines in muscle strength are primarily observed in concentric movement as opposed to isometric and eccentric movements (Vandervoort, 2002). Further, considering the larger diameter of type II fiber area compared to type I muscle fibers (Brooke and Kaiser, 1970) and the age-related reduction in type II fiber area (Lexell and Downham, 1992), it is unsurprising that aging attenuates muscular force capacities. This overall reduction in muscle strength is gradual throughout the lifetime but muscle strength can decrease ~ 1-2% per year after the 6^{th} decade (Vandervoort, 2002). Therefore, it might be prudent to attenuate any age-related declines in muscle strength before the 6^{th} decade. Finally, although the exact mechanism related to the reduction in force generation capacity is unclear, it seems that the primary contributing factors contributing are reduced muscle mass and size specifically due to reduction in type II fiber size.

In addition to the importance of muscle force for human movement, muscle power is critical factor related to gait speed (DeVita and Hortobagyi, 2000; Hortobagyi et al., 2016). The

ability of muscles to generate power is influenced by the morphological characteristics of the muscle and its ability to generate force (Morse et al., 2005; Thom et al., 2007). Power is dependent upon both force and velocity, so therefore, both muscular force and contractile velocity must be maintained in order to retain muscle power. Contractile velocity is related to muscle fascicle length (Thom et al., 2007) and older adults tend to have shorter muscle fascicles compared to younger adults (Stenroth et al., 2012; Thom et al., 2007). Age-related atrophy of skeletal muscles and loss of strength extends the effects of altered central and peripheral nervous system innervation (Doherty, 2003; Gerstner et al., 2017; Lynch, 2010; Macaluso and De Vito, 2004; Vandervoort, 2002). However, the behavior of the intrinsic muscle-tendon unit is fundamentally a component of mobility and can affect force production and metabolic cost during locomotion (Biewener and Roberts, 2000; Hof et al., 2002; Sultana et al., 2012). The tendon transmits force to the skeleton to create joint movement and exhibits time-dependent extensibility and recoil. At a given force applied to a muscle-tendon unit (MTU), a less compliant tendon may result in greater elongation of the muscle fascicle (Magnusson et al., 2008). During locomotion the medial gastrocnemius (GM) fascicles perform the same action along the same length, however, distal fascicles tend to shorten more and act at greater pennation than more proximal fascicles (Lichtwark et al., 2007). For instance, during walking, a shorter muscle fascicle and a more compliant tendon are utilized when compared to running (Lichtwark and Wilson, 2008). During running, fascicles shorten through the stance phase corresponding to increased strain of the series-elastic element consisting of the Achilles tendon and aponeurosis (Lichtwark et al., 2007). Factors related to changes in fascicle length can alter the gearing through which muscle fiber operate during contractions and therefore affect its capability to produce muscle force and velocity (Azizi et al., 2008). Despite the deterioration of

neuromuscular and morphological function with aging, exercise may, mitigate these age-related declines in overall function, and improve quality of life.

Influence of Exercise on Aging

It is evident that aging reduces overall function because of multiple negative age-related changes in neuromuscular, musculoskeletal, and cardiovascular factors. Repetitive practice enhances motor task organization which may be a mediator for adaptions to the musculoskeletal system (Mulder et al., 2002; Pantoja et al., 2016; Taubert et al., 2015). For instance, preserved fiber morphology and ultrastructure of intercellular organelles involved in calcium handling and ATP production preserve fiber size because of fiber rescue by reinnervation is found in active seniors compared to sedentary seniors (Zampieri et al., 2014). Supplementary power training increases EMG amplitude explaining ~33% of increases in isometric strength (Beijersbergen et al., 2017), concentric one repetition maximum (Häkkinen et al., 2001), and total muscle area (Frontera et al., 1988). In addition, a moderate intensity endurance training program is effective in improving speed of muscular contraction, walking velocity, VO_2max, and standing balance in individuals 60 to 72 years of age (Brown, 2003). Endurance exercise training improves cardiovascular function in older adult populations (Hill et al., 1993). Specifically, endurance exercise may lead to an increase in VO_2max (O'Neill et al., 2016). It seems that exercise may be sufficient to mitigate muscle and cardiovascular function with increased age despite inevitable deterioration of cardiovascular, neuromuscular, and musculoskeletal health; however, these reductions may increase the risks of lower extremity injury and consequently hindering the benefits of exercise on cardiovascular function.

1.2.2 The Aging Runner

Considering the increase in running participation among older adults, it would be useful to understand the influence of running in aging adults on injury risks, cardiovascular factors, musculoskeletal tissue morphology, and running biomechanics.

Running Injuries

Running-related injuries more commonly occur among distance runners (Fields, 2011) and novice runners (Nielsen et al., 2012). In addition, older runners are even more likely to suffer RRI compared to younger runners (Matheson et al., 1989; McKean et al., 2006). But, runners with less than three years of running experience are at a greater risk of injury compared to more experienced runners (Macera et al., 1989). More experienced runners are typically more knowledgeable and understand periodized training programs, and are more likely to avoid unsafe progression of running volume and intensity (Nielsen et al., 2012).

The plantarflexor complex (PFC) and tibia are amongst the most common overuse injury sites in older runners (McKean et al., 2006). These injuries may be related to intrinsic reductions in plantarflexor strength and passive dorsiflexion range of motion (Mahieu et al., 2006). Moreover, skeletal overuse injuries are common in middle-aged runners specifically to the tibia, femoral neck, and femoral shaft (Fields, 2011). These skeletal injuries may be related to smaller knee flexion excursions during the stance phase of running in older compared to younger runners (Bus, 2003) since less knee flexion suggests greater skeletal contribution to stiffness (DeVita and Hortobagyi, 2000b) .The development of running injuries in older runners is a critical problem considering the positive health benefits associated with running.

Running and Cardiovascular Health

Distance running performance begins to decline around 35 years of age (Leyk et al., 2007; Tanaka and Seals, 2008). Normal aging is associated with a decline in maximal heart rate (Tanaka et al., 2001), physiological determinants of endurance performance (e.g., stroke volume, maximal oxygen consumption, and running economy) (Allen et al., 1985; Tanaka et al., 2001; Tanaka and Seals, 2008), and ultimately the deterioration of preferred and maximal running speed (DeVita et al., 2016; Korhonen et al., 2009). Running economy is a confounding factor explaining ~64% of the variation in 10-km running performance. Running for exercise may mitigate decline in running economy in runners 65 years of age (Beck et al., 2016), and improve walking economy in older adults ~69 years of age when compared in active counterparts (Ortega et al., 2014). In addition to resulting in positive cardiovascular benefits, running also influences the morphology and mechanical characteristics of muscles as runners age.

Running and Muscle Morphology and Characteristics

Since muscle tendon unit (MTU) adaptations are load dependent (Arampatzis et al., 2010; Magnusson et al., 2008), it is logical that running exposure seems to stimulate adaptation of the Achilles tendon (Stenroth et al., 2016). Further, considering the adaptability of the plantarflexor MTU to loading (Reeves et al., 2002; Reeves et al., 2005) and the load experienced during each running step, functional properties of muscle and tendon (e.g., stiffness of tendon) may be preserved regardless of age as a result of running (Stenroth et al., 2016). For instance, mechanical stiffness of the Achilles tendon is greater at in older runners compared to non-runners (Magnusson et al., 2001). Relatedly, medial gastrocnemius (GM) resting pennation angle is greater in runners in both older and younger runners (Karamanidis and Arampatzis, 2005), which may result in shorter fascicle length (i.e., greater muscle tone contributing to higher

PFC stiffness) considering the influence of pennation angle on the calculation of fascicle length (Kubo et al., 2003). However, contradicting literature suggest that pennation angle of GM is not affected by running, but that soleus fascicle length is longer in older endurance runners compared to old non-runners (Stenroth et al., 2016), this could be due to training status of the participants. Running intensity also appears to play a vital role in GM morphology as sprint-trained older runners have similar GM fascicle length compared to untrained young control (Stenroth et al., 2016). Although the exact mechanism by which running affects the morphology is unclear, running appears to influence morphological characteristics of the PFC which may in turn affect the running biomechanics of older runners (Karamanidis and Arampatzis, 2006) .

Running Biomechanics

It is reasonable to suggest that age-related changes in plantarflexor kinetics (Thom et al., 2007) may be related to the aforementioned age-related changes in morphological and architectural characteristics of the PFC with aging. Considering that the propulsive phase of gait primarily requires concentric muscle action (DeVita and Hortobagyi, 2000), it is unsurprising that peak vertical push-off and peak propulsive GRF (Bus, 2003) are smaller in older compared to younger runners. These reductions in of muscle power with aging likely contributes to the reported age-related declines in ankle plantarflexor mechanical output during gait (DeVita et al., 2016; Hortobagyi et al., 2016). The decline in ankle plantarflexor mechanical output and peak vertical and propulsive GRF during the late stance phase (i.e., primarily concentric muscle action) ultimately leads to slower preferred and maximal running speeds (DeVita et al., 2016)

Even with these age-related changes in lower extremity running biomechanics, running-specific training (i.e., form-focused training) increases sagittal plane moments and powers compared to self-directed and group-based conventional running training (Kumar et al., 2015).

On the other hand, active elderly adults walk with similar ankle moments but with larger hip extension moments likely to compensate for reduced PFC muscle function which enables them to maintain support torques and gait velocity when compared to inactive elderly adults (Kuhman et al., 2018; Savelberg et al., 2007). In running, when weekly running volume is similar between middle-aged (~58years) and younger (~28years) runners ankle plantarflexor moments are still lower while peak positive ankle powers are similar between age groups (Paquette and DeVita, 2018). Interestingly, both plantarflexor moments and peak positive ankle powers are similar in middle-aged (~58years) compared to younger runners (~30years) when preferred running pace is similar between age groups (Paquette and DeVita, 2018). These findings suggest that running speed (i.e., pace) may have a greater influence on preserving plantarflexor mechanical output than average weekly running volume. Additionally, no differences in lower extremity running mechanics have been observed in runners between the ages of 15-54 years who have different lifetime running experience even when accounting for speed variations (Agresta et al., 2017). Therefore, although it appears that running exposure may combat age-related changes in running biomechanics, it is currently unclear how running training and lifetime experience affect running mechanics in older runners.

1.3 Literature Gaps and Limitations

Considering the importance of training stimuli on endurance performance and muscle function in older athletes, gait biomechanics and plantarflexor morphology maybe preserved to cope with the mechanical demands of running. Although training volume and intensity may play a role in the preservation of ankle kinetics and morphology, a question remaining is whether lifetime running exposure influences the running biomechanics and muscle characteristics of older runners.

1.4 Research Questions and Hypotheses

Based on current literature findings and limitations, the following research question and hypotheses were formulated:

Research Question: How does lifetime running exposure influence ankle kinetics during running and medial gastrocnemius morphological properties in older runners with different lifetime running exposures.

Hypotheses: It is hypothesized that older runners with greater lifetime running exposure will run with larger ankle plantarflexor moments and peak positive ankle powers compared to runners with less lifetime running exposure. It is also, hypothesized that older runners with greater lifetime running exposure will have larger pennation angles, shorter fascicles, and greater fascicle stiffness of the medial gastrocnemius compared to runners with less lifetime running exposure.

CHAPTER II

Ankle Kinetics and Plantarflexor Morphology in Older Runners with Different Lifetime Running Exposures

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Introduction

The number of adults over 40 years of age participating in running races rose 21% between 1980 and 2013 while 19% of U.S. marathon participants in 2013 were over the age of 55 (Lamppa, 2013). Considering the declining health status of North Americans over the last decades, running participation is important since it is associated with lower risks of death from cardiovascular disease and all causes of cardiovascular mortality (Lee et al., 2014), lower body mass index (Williams, 2013), and better overall physical performance regardless of age (Tanaka and Seals, 2008; Tarpenning et al., 2004). However, numerous physiological and biomechanical factors are affected by that may ultimately reduce movement function and participation in exercise. Therefore, a delineation of factors that can influence the physiology and biomechanics of aging runners may help attenuate age-related declines in function.

Aging is associated with a reduction in muscle volume (Morse et al., 2005), total number of muscle fibers, cross-sectional area (Lexell et al., 1988), and reductions in fiber fascicle length and pennation angle at the plantarflexor complex (PFC) (Karamanidis and Arampatzis, 2006; Reeves et al., 2002; Stenroth et al., 2012). These age-related reductions may explain why older adults typically generate less maximum plantarflexor force compared to younger adults (Thom et al., 2007). Since mechanical and morphological properties of gastrocnemius can influence their

capacity to generate torque at the ankle (Thom et al., 2007), older runners have a reduced ability to generate ankle plantarflexor angular power and work compared to younger runners (DeVita et al., 2016; Fukuchi et al., 2014). These age-related reductions in ankle kinetics are paralleled by lower push-off vertical (GRF) (Kline and Williams III, 2015), anterior propulsive GRF (Korhonen et al., 2009), and step length (DeVita et al., 2016) in older compared to younger runners. Consequently, aging leads to slower preferred (DeVita et al., 2016) and maximal (Korhonen et al., 2009) running speeds. Age-related decline in maximal and submaximal cardiorespiratory function, strength, and power (Quinn et al., 2011), may in part be responsible for slower running speeds during training. Ultimately, maintenance of ankle joint kinetics, plantarflexor morphology, and mechanical properties may be of importance to maintain function during activities of daily living (Stenroth, Sillanpää et al., 2015).

Repetitive practice enhances motor organization that may mediate recovery and adaptions of the musculoskeletal system (Mulder et al., 2002; Taubert et al., 2015) . For example, endurance runners have greater medial gastrocnemius pennation angles compared to non-active individuals (Karamanidis and Arampatzis, 2005). A greater pennation angle may result in shorter fascicle length (Kubo et al., 2003), and shorter fascicles are more fatigue-resistant during submaximal contractions to failure (Mademli and Arampatizis, 2008). Considering that soleus muscle fascicles are shorter in endurance runners (Stenroth et al., 2016), running exposure may enhance resistance to muscle fatigue by reducing PFC fascicle length. This work provides further evidence that frequent running exposure may influence plantarflexor muscle morphology (Stenroth et al., 2016), and these positive morphological changes may be related to the preservation of ankle joint kinetics normally degraded by aging. In fact, weekly running volume and pace appear to have positive influences on ankle joint kinetics in the older runner (Paquette

et al., 2018) and highly trained older runners exhibit similar leg and vertical stiffness in younger similarly trained runners (Pantoja et al., 2016). These findings suggest that training exposure may influence running biomechanics in older runners. Although lifetime running (15 to 53 years of age) exposure does not appear to influence running mechanics in distance runners (Agresta et al., 2017), it is currently unclear how it may influence ankle kinetics during running and plantarflexor morphological characteristics in runners over 50.

The purpose of this study was to examine the influence of lifetime running exposure one ankle kinetics during running and on medial gastrocnemius morphology properties in older runners with different lifetime running exposures. We hypothesized that older runners with greater lifetime running exposure would run with larger ankle plantarflexor moments and peak ankle positive powers compared to runners with less lifetime running exposure. We also hypothesized that older runners with greater lifetime running exposure would have larger pennation angles, shorter fascicle lengths, and greater medial gastrocnemius stiffness compared to runners with less lifetime running exposure.

Materials and Methods

Participants

Twenty-one runners (9 women and 12 men) over the age of 50 years were recruited for this study (Table 1). Participants were included if they had no lower extremity injuries within the past 12 months, if they ran at least 10 miles per week incorporating no less than three runs per week, and if they had no metabolic or orthopedic conditions. Prior to participation, participants were informed of all procedures, potential risks, and benefits associated with the study through

both verbal and written form in accordance with the procedures approved by the University Institutional Review Board for Human Participants Research.

Procedures

All participants completed a questionnaire regarding their training experience and other training-related details. Based on our studied population sample of runners, participants were then separated into low (LRE) or high (HRE) lifetime training exposure (Table 1). Lifetime training exposure was defined as the product of number of lifetime running years, average weekly lifetime running mileage, and average number of weeks running per year (Agresta et al., 2017). Participants also completed the *Foot and Ankle Outcome Score* (FAOS) survey to assess ankle joint health, a potential confounding factor in our analysis (Martin and Irrgang, 2007; Roos et al., 2001). Body height (m) and mass (kg) were recorded for all participants.

Since the foot is the first point of contact with ground during gait, differences in foot structure and characteristics may result in differences in lower extremity mechanics (Nigg et al., 1993; Powell et al., 2014; D. S. Williams et al., 2004). The *Arch Height Index Measurement System*™ was used to obtain right foot during sitting and bilateral standing, to enable the computation of the arch height index (AHI) (D. S. Williams and McClay, 2000), since high-arched runners tend to run with different joint kinetics compared to low-arched runners (Powell et al., 2016).

To establish a target PFC force during testing, the Arch Height Index Measurement System™ (AHIMS) was used to obtain right foot measurements of the right leg while standing. Achilles tendon moment arm was operationally defined as the antero-posterior differences between the lateral malleolus and the posterior aspect of the Achilles tendon over the skin

(Figure 1). The resistance moment arm was measured as the distance between the point of force application during ultrasound measurement (i.e. first metatarsal) and lateral malleolus (Figure 1).

Participants then completed a five-minute running warm-up at their preferred running speed on a treadmill (Excite+ RUN NOW, TechnoGym, USA). All participants wore standard lab shoes (New Balance, MX623) during running tests. A 9-camera three-dimensional (3D) motion capture system (240 Hz, Qualisys AB, Göteburg, Sweden) and a 3D force platform (1200Hz, AMTI, Watertown, MA, USA) were used to obtain 3D kinematics and ground reaction forces, respectively. These data were collected in synchrony using Qualisys Track Manager Software (Qualisys AB, Gotenburg, Sweden). Data were collected on the right leg of each participant using spherical reflective markers placed on specific anatomical landmarks to define each segment and thermoplastic shells to track segment movement. The pelvis was defined by the iliac crests (aligned vertically with greater trochanters) and greater trochanters, and the hip joint center was calculated at the location of one-quarter the distance between ipsilateral and contralateral greater trochanter (Weinhandl and O'Connor, 2010). The thigh was defined with the greater trochanter, the calculated hip joint center, and femoral epicondyles. The shank was defined with the femoral epicondyles and the malleoli. Additionally, the foot was defined with the malleoli and the first and fifth metatarsal heads. A thermoplastic shell with three reflective markers were placed on the heel of the right shoe to track the segment. Finally, one reflective marker was placed on the heel of the left shoe to allow step length measurements. A one-second static calibration trial was recorded before the start of data collection to define joint centers and segment coordinate systems and dimensions. Subsequent to anatomical marker removal, participants performed five running trials over a 25m runway at a gait speed of 2.7m/s (±5%)(Fukuchi et al., 2014; Fukuchi et al., 2016; Paquette and DeVita, 2018). Gait speed was

monitored using an electronic timer (54035A, Lafayette Instruments Inc., IN, USA) and two photocells (63501 IR, Lafayette Instruments Inc., IN, USA) mounted on tripods at shoulder height and perpendicular to the laboratory runway at a three-meters interval. Participants performed two-to-three practice trials to allow them to achieve the desired testing speed while contacting the force platform with their right foot without visual targeting.

Following the running trials and ~10min rest period, assessments of gastrocnemius morphology and mechanical characteristics were performed. A force transducer (Model MLP-1k, Transducer Techniques, Temecula, CA) attached in-series with a metal chain was secured underneath the table (Figure 2). On the other end, the metal chain was attached to a cuff secured to a wooden platform to stabilize the foot during testing (Figure 2). Muscle morphological characteristics of plantarflexors were assessed using a linear array ultrasound transducer (L12-4MHz Philips, Lumify; USA), positioned along the longitudinal axis of the right medial gastrocnemius (MG) at 30% of the distance between the medial malleolus and the tibia (Pamukoff and Blackburn, 2015) which is approximately 50% of muscle length (Kubo et al., 2003). The ultrasound probe was secured to the leg using Velcro straps attached to a custom-designed plastic mold (Autodesk, Inventor Pro) and fabricated with a 3D printer (Makerbot 5th Generation Replicators, USA) to ensure a perpendicular alignment with the leg. With this arrangement, the only force acting on the probe was gravity thereby reducing variations in probe application pressure over the skin. Participants were secured in the prone position to a treatment table using a harness system (Solo-Step System, USA) to avoid any longitudinal movements of the body during testing (Figure 3). Further, the harness system tension could be manipulated to move the participant in a position to ensure a 90-degree ankle joint angle (Figure 2 & 3). Before experimental testing, participants were asked to gradually push against the wooden platform

while straps were tightened to ensure that the ankle joint remained within three degrees of the initial 90-degree position during testing. For GM stiffness calculations, muscle fascicle length was measured at different plantarflexor tensile forces. Specifically, these plantarflexor tensile forces were equivalent to 25%, 50%, 75%, and 100% of previously reported forces of plantarflexors during running (Besier et al., 2009). To obtain individual participant estimated plantarflexor force (PFforce), the previously reported peak plantarflexor (i.e., sum of medial and lateral gastrocnemius) force during running ($24.15 N \cdot kg^{-1}$) was multiplied by each participant's body mass. The force transducer target tensile force during testing was calculated from each participant's Achilles tendon moment arm (ATr) and resistance moment arm (Rr) (location of force application below the 1st metatarsal) measured earlier in the testing session, and the estimated PFforce (Equation 2).

Equation 2: $$Target\ Forces = \frac{(PFforce\ x\ ATr)}{Rr}$$

During testing, participants were asked to produce the 25%, 50%, 75%, and 100% target tensile forces streamed in real-time with Qualisys Track Manager Software on a computer screen positioned in their line of vision. Participants were asked to gradually increase their force output by pushing against the foot platform until the target force threshold was reached. They were asked to hold this force output for approximately two to three seconds. Two images per target tensile force of the MG were captured separately at rest and during isometric contractions for each tensile force percentage. Rest periods of approximately 30 seconds were provided between contractions, while ultrasound images quality was verified. If the quality of the images was deemed to be of poor quality (i.e., blurry), an additional image was taken.

Data Analyses

Visual 3D (C-Motion, Germantown, MD) was used to compute 3D joint kinematic and kinetic variables. Kinematic data were interpolated using a least-squared fit of 3rd order polynomial with a three-data point fitting and maximum gap of 10 frames. Kinematic and GRF data were filtered using a fourth-order Butterworth low-pass filer with cut-off frequencies of 8 and 40 Hz, respectively. A right-hand rule with a Cardan rotational sequence (X-y-z) was used for 3D angular computations, where x represents the sagittal plane, y represents the frontal plane, and z represents the transverse plane. A vertical GRF threshold of 20N was used to define the start and end of the stance phase. The ankle, knee and hip joint angular kinematic and kinetic variables were expressed in the shank, thigh, and pelvis coordinate systems, respectively. Newtonian inverse dynamics was used to compute net internal joint moments ($Nm \cdot kg^{-1}$) during stance. The 3D angular joint powers ($W \cdot kg^{-1}$) were computed as the dot product of joint moments and angular velocities. Step length was computed as the anterior-posterior distance between the left heel marker at time of left foot contact and a right foot marker at time of right foot contact. Dependent running biomechanics variables included: step length; peak propulsive and vertical push-off (i.e., active peak) GRF; peak lower limb joint extensor moments; peak positive lower limb joint angular powers. The average of each dependent variable from the five running trials was used in statistical analyses.

Ultrasound images and measurements were completed by the same sonographer to eliminate potential inter-tester reliability issues. Although stability reliability of the ultrasound measurements was not assessed for the current sample, it was obtained earlier during pilot testing for the same measurements, by the same sonographer using the identical setup, and for comparable subjects. Pennation angle intra-class correlation coefficients using a two-way mixed model (Koo and Li, 2016) ranged between 0.61 and 0.93 for six young participants. The two

images per contraction condition were analyzed separately using an open-source program (Image J 1.44b, National Institutes of Health). GM pennation angles (θ) were measured as the angle of insertion of muscle fascicle into the deep aponeurosis (Figure 4). Fascicle length (FL) was calculated using a previously reported equation (Kubo et al., 2003) (Equation 3; Figure 4). Each measurement was taken three times for each of the two images per contraction condition and the average of the six measurements was used to compute the change in FL (ΔFL) between FL rested and FL contracted (Equation 4) for each target force.

Equation 3: $$FL\ (mm) = \frac{MT(mm)}{Sin\ \theta}$$

Equation 4: $$\Delta FL\ (mm) = FL\ rested - FL\ contracted$$

Due to tension on the strain gauge and inevitable movement of the ankle joint during the rested condition, the initial force reading from the force-time curve was variable and often fluctuated between measurements. To control for this fluctuation, force values at rest were subtracted from their respective target forces to establish a "zero" baseline prior to each contraction at all four percentages. Finally, transducer forces at each contraction percentage were plotted against the GM ΔFL from the resting and contracting images and GM stiffness was calculated as the slope of the force and ΔFL curve.

Statistical Analyses

Independent *t*-tests were used to compare biomechanical variables and plantarflexor morphology and characteristics, and participant and training characteristics between groups. Data normality was assessed using the Kolmogorov-Smirnov tests (p<0.05). If data were not normally distributed a Mann-Whitney non-parametric test was used to compare group differences. Significance was set at an alpha level of 0.05. Cohen's *d* effect sizes were also calculated for

effect magnitude of group mean differences (i.e., small: $d \leq 0.6$, moderate: $0.6 > d < 1.2$; large: $d \geq 1.2$ (Hopkins, 2018)

Results

Participant Characteristics

We confirmed that the HRE group had greater lifetime running exposures, and more lifetime years of running and, higher lifetime average weekly volume compared to the LRE group (Table 1).

Running Biomechanics

No group differences were observed for step length; peak propulsive force; ankle, knee and hip joint peak moments and; for ankle and knee joint peak positive angular powers (Table 2). However, peak positive hip power was greater in the HRE compared to the LRE group (Table 2).

Medial Gastrocnemius Morphology

With the exception of the resting measure prior to the 25% contraction, a greater MG pennation angle was observed in the LRE group compared HRE group for all resting and contracted conditions (Table 4). No differences in FL and ΔFL at any of the rested or contracted conditions were observed (Table 4). Target tensile forces during testing were not different between group (Table 4) which was expected considering they are directly related to body mass and no group differences were observed in body mass (Table 1). MG stiffness was also not different between groups (Table 4).

Foot and Ankle Outcome Score and Arch Measures

No differences for any of the FAOS outcomes and for the arch measures were observed between groups (Table 5).

Discussion

The purpose of the current study was to assess the influence of lifetime running exposure on ankle kinetics during running and medial gastrocnemius morphological properties in older runners. Considering the popularity of running as a mode of aerobic exercise and increase in running participation in older adults, understanding the cumulative lifetime effects of running is important.

We hypothesized that older runner with high lifetime running exposure would run with larger peak plantarflexor moment and positive ankle power compared to runners with low lifetime exposure. Contrary to this hypothesis, peak plantarflexor moment and peak positive power, in addition to step length and peak propulsive GRF, were similar between lifetime-running exposure groups. This suggests that more lifetime running exposure in older runners does not help preserve ankle mechanical output during running. This finding is consistent with recent evidence that lifetime running exposure does not influence spatio-temporal and joint kinematics and GRF variables during running in runners between 15-54 years (Agresta et al., 2017). It therefore seems that running mileage exposure has limited effects on ankle kinetics and GRF variables in runners between approximately 15 and 70 years. Further, although other studies did not report lifetime running exposure of their middle-aged or older runners, the peak plantarflexor moment (~2.2 – 2.3 $Nm \cdot kg^{-1}$) and peak positive ankle power (~6.8 – 7.2 $Nm \cdot kg^{-1}$) of both groups in the current study are similar to previously reported ankle moments (~2.1 – 2.3 $Nm \cdot kg^{-1}$) and powers (~7.3 – 7.6 $Nm \cdot kg^{-1}$) (DeVita et al., 2016; Paquette et al.,2018). Although we did not include young participants in this study, these values confirm that older runners in our study ran with ankle kinetics that are lower than magnitudes typically reported in young runners (DeVita et al., 2016; Kuhman et al., 2016; Paquette et al., 2013; Sinclair, 2014). Recent research

proposed the hypothesis that preferred running pace (i.e., intensity) may have a greater influence on ankle mechanical output than average weekly running volume in middle-aged runners (Paquette et al., 2018). Thus, the similar self-reported preferred training paces (Table 1) may partly explain the similar ankle kinetics between groups in the current study. Our current findings may suggest that more lifetime running exposure measured using weekly mileage in runners over 50 years may not be sufficient to alter peak ankle moments and peak powers. Perhaps a better lifetime training exposure measure would be of the cumulative average intensity of running, or pace, throughout a lifetime.

The similar knee joint kinetics between groups was expected but interestingly, peak positive hip power was larger in the HRE compared to LRE group although peak hip flexor and extensor moments were not different between groups. The greater hip concentric power may be an undertone for greater hamstring injuries (i.e., hip extensors) in older runners (McKean et al., 2006) since more active older adults use more hip work during walking (Savelberg et al., 2007, Kuhman et al., 2018). Active older adults who run twice per week walk with greater lower extremity support moment (i.e., sum of all joints) compared to inactive older adults (Savelberg et al., 2007). Although the peak ankle and hip moments of active older adults were not statistically different, they were slightly greater in the active compared to inactive older adults which explains the greater support moment. This finding is similar to recent reports that older individuals with higher physical capacity walk with greater hip mechanical output compared to less physically capable older adults (Kuhman et al., 2018). In the current study, the larger hip positive power during running suggests that more lifetime running exposure may result in an increase in concentric hip joint involvement. However, considering the cross-sectional design of the current study, it is difficult to conclude whether more concentric hip joint involvement is the

result of more lifetime running exposure or that runners with more concentric hip joint involvement have been able to run more lifetime volume. It is possible that, considering the size and force production capacity of hip extensor musculature, more concentric hip involvement could be a strategy employed by older runners who have run high lifetime mileage to compensate for the age-related decline in ankle plantarflexor mechanical outputs (DeVita et al., 2016; Fukuchi et al., 2014; Karamanidis and Arampatzis, 2007). Further, reduced mechanical output from the hip rather than from the knee limits maximal running velocity in older and middle-aged compared to young individuals (Kulmala et al., 2014) and thus, increased hip mechanical output may be beneficial to maintain running speed with age or in this case, with greater running volume.

We also expected that runners with higher lifetime running exposure would have larger pennation angles, shorter fascicle length, and greater stiffness of the medial gastrocnemius when compared to runners with low lifetime running exposure. Our hypothesis was not supported as no differences in fascicle length and stiffness were observed between groups despite a smaller pennation angles in HRE compared to LRE group. These observations are consistent with previous findings that no change in GM fascicle length, despite a slightly larger GM pennation angle, are observed in runners compared to non-active individuals (Karamanidis and Arampatzis, 2006). However, (Stenroth et al., 2016) have reported that older endurance or sprint-trained adults have similar pennation angles to older inactive adults despite differences in training exposures (Stenroth et al., 2016). Conflicting evidence may be the result of different groups compared in all studies (e.g., training exposures, spring compared to endurance, and age differences), and it is evident that longitudinal studies are needed to understand the influence of lifetime training exposures on morphological properties of muscles.

This study has several limitations. First, the cross-sectional design of the current study makes it impossible to truly understand the longitudinal effects of lifetime running exposure especially since participants recall of training history may have not have been completely accurate. Second, gastrocnemius tensile forces used during MG morphological testing for each participant were estimated from previously reported average peak body mass normalized MG forces during over-ground running (Besier et al., 2009). The forces used in the current study were directly related to body mass and may not have accurately depicted individual MG forces during running. Third, measures of ATr may be overestimated due to the nature of the measurement. Moreover, the estimation of Rr was taken from the lateral malleolus and may not be representative of the ankle joint center of rotation. Finally, previous training history (i.e. resistance training, sprint training, hill running, etc…) of older runners was not accounted for in this study. These training characteristics may have an influence on neurosmuscular factors, joint moment and power generation, and muscle morphological properties.

Perspective

Lifetime running exposure in older runners does not appear to influence ankle and knee kinetics but older runners with higher lifetime running exposure run with greater hip concentric power compared to those with lower lifetime running exposure. This finding may suggest a hip-focused strategy employed by older runners who have run high lifetime mileage to potentially compensate for the well-reported age-related declines in ankle plantarflexor mechanical outputs. Lifetime running exposure does not appear to influence morphological and mechanical properties of MG despite differences in pennation angles. This cross-sectional study provides preliminary data regarding the influence of lifetime running exposure. However, it is clear that

longitudinal cohorts are necessary to truly understand the influence of lifetime running exposure on lower limb joint kinetics during gait, and muscle morphology in aging runners.

CHAPTER III
GENERAL RECOMMENDATIONS

3.1 Summary

The aim of this study was to assess ankle kinetics and MG morphology in older runners with different lifetime running exposure. A better understanding of the influence of increased training exposure on joint biomechanics and muscle function can provide more mechanistic explanations for the influence of training exposure on gait function. By doing this research we may be able to improve gait function and allow aging adults to maintain a more youthful locomotor function and movement intensity during daily activity and exercise which may ultimately help preserve cardiovascular and musculoskeletal health to ensure healthier aging and quality of life. Thus, data from this work may eventually aid clinicians, coaches, and researchers to decrease risks of injury and optimize running mechanics with aging.

The findings form the current study suggest that higher lifetime running exposure does not affect age-related deterioration in ankle propulsive capabilities. However, older runner with higher lifetime running exposure run with greater hip concentric power compared to those with lower lifetime running exposure. This finding may suggest a hip-focused strategy employed by older runners who have run high lifetime mileage to potentially compensate for the well-reported age-related declines in ankle plantarflexor mechanical outputs.

3.2 Recommendation for future research

Findings from this study have summoned new research questions for future studies. Our data suggest that ankle propulsive function deficits are unaffected by higher lifetime running exposure but that more hip joint concentric involvement may be a strategy used by older runners who have more lifetime running exposure. However, since middle-aged runners who have

similar preferred running paces as younger runners run with the same ankle mechanical output (Paquette et al., 2018), future studies should investigate the influence of different exposures of running intensity in older runners, instead of mileage, on joint kinetics during running. Further, in this study we only assessed the MG morphological characteristics and did not assess the characteristics of soleus, lateral gastrocnemius, and the Achilles tendon which contribute to ankle mechanical output during locomotion. Future studies should include these measurements to gain a better understanding of lifetime training exposures on the morphological factors contributing to muscle-tendon mechanics during running in older runners. Moreover, future studies should also focus on training interventions such as power and strength training to target improvements in ankle mechanical output during gait in older and middle-aged runners (Crowell and Davis, 2011; Agresta et al., 2017). Continued research on this topic should eventually help scientists and clinicians get closer to attenuating age-related declines in locomotor function that ultimately negatively influence overall health and quality of life.

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APPENDICES

Appendix A: Tables

Table 1: Participant and training characteristics for both low running (LRE) and high running exposure (HRE) groups (means ± SD).

Characteristics	**LRE**	**HRE**	***p*-value**	***d***
Age (years)	59.0±8.0	62.0±7.0	0.45	0.42
Height (m)	1.73±0.1	1.67±0.1	0.18	0.64
Mass (Kg)	72.7±9.6	67.0±15.5	0.31	0.48
Body Mass Index ($Kg \cdot m^{-2}$)	24.3±2.8	24.0±3.8	0.36	0.23
Years of lifetime Running *	10.0±4	37.0±8.8	<0.001	4.39
Weekly Volume over lifetime ($miles \cdot week^{-1}$) *	18.0±4.0	25.7±6.1	0.002	1.61
Weekly Volume in Past Years ($miles \cdot week^{-1}$)	50.6±3.0	49.3±3.4	0.32	0.44
Years without running	0.3±0.6	2.2±3.3	0.06	0.95
Lifetime Running Exposure (miles) *	8834±3823	45984±14967	<0.001	3.85
Preferred Running Pace ($min \cdot mile^{-1}$)	11.0±1.5	10.1±2.1	0.11	0.57

Notes: *: $p<0.05$; *d*: Cohen's effect size

Table 2: Peak propulsive force, peak lower limb joint torques, and peak positive joint powers for both low running (LRE) and high running exposure (HRE) groups (mean±SD).

Variables	**LRE**	**HRE**	***p*-value**	***d***
Step Length (m)	0.98±0.07	0.97±0.08	0.67	0.14
Peak propulsive force (BW)	0.21±0.03	0.21±0.04	0.73	0.00
Peak ankle plantarflexor moment ($Nm \cdot kg^{-1}$)	-2.2±0.2	-2.3±0.4	0.36	0.44
Peak ankle positive power ($Nm \cdot kg^{-1}$)	6.8±0.8	7.2±2.0	0.58	0.29
Peak knee extensor moment ($Nm \cdot kg^{-1}$)	2.0±0.4	1.9±0.5	0.08	0.20
Peak knee positive power ($W \cdot kg^{-1}$)	3.0±0.8	3.1±1.0	0.86	0.08
Peak hip flexor moment ($Nm \cdot kg^{-1}$)	0.7±0.1	0.7±0.2	0.69	0.22
Peak hip extensor moment ($Nm \cdot kg^{-1}$)	-1.7±0.5	-1.9±0.5	0.66	0.39
Peak hip positive power ($W \cdot kg^{-1}$) *	2.2±1.3	3.1±1.1	0.01	0.84

Notes: *: $p<0.05$; Step length: anterior distance between right heel position at time of right foot contact and left heel position at time of left foot contact; *d*: Cohen's effect size.

Table 3: Morphological measurements of medial gastrocnemius at rest and contracted for both low running (LRE) and high running exposure (HRE) groups (mean±SD).

Variables	**LRE**	**HRE**	***p*-value**	***d***
25% Contraction				
Θ_R (°)	19.8±2.9	18.0±1.4	0.07	0.82
Θ_C (°) *	22.5±3.6	19.7±2.1	0.03	1.01
FL_R (mm)	56.0±14.1	52.7±8.3	0.94	0.29
FL_C (mm)	48.8±13.9	47.5±7.3	0.78	0.12
50% Contraction				
Θ_R (°) *	19.9±2.9	15.8±5.9	0.03	1.00
Θ_C (°) *	23.9±4.5	20.6±1.4	0.02	0.95
FL_R (mm)	55.1±13.6	53.8±9.2	0.62	0.12
FL_C (mm)	45.7±15.1	44.8±6.7	0.86	0.08

75% Contraction				
Θ_R (°) *	20.1±3.0	17.5±1.5	0.02	1.08
Θ_C (°) *	24.9±4.6	21.5±1.7	0.03	0.99
FL_R (mm)	54.6±13.2	54.0±8.3	0.39	0.02
FL_C (mm)	43.3±14.1	43.4±6.5	0.98	0.04
100% Contraction				
Θ_R (°) *	19.8±2.8	17.8±1.5	0.04	0.93
Θ_C (°) *	26.6±5.5	22.5±2.3	0.03	0.98
FL_R (mm)	55.2±13.6	53.6±8.1	0.57	0.15
FL_C (mm)	41.4±14.1	42.1±7.0	0.88	0.07

Notes: *: $p<0.05$; Θ_R: pennation angle at rest; Θ_C: pennation angle during contractions; FL_R: muscle fascicle length at rest; FL_C: muscle fascicle length during contractions; *d*: Cohen's effect size.

Table 4: Change in muscle fascial length (ΔFL) between rested and contracted conditions, tensile forces (TF) in contracted conditions, and stiffness for both low running (LRE) and high running exposure (HRE) groups (mean±SD).

Variables	**LRE**	**HRE**	***p*-value**	***d***
ΔFL at 25% (mm)	7.2±2.9	5.2±2.4	0.11	0.77
ΔFL at 50% (mm)	9.4±3.1	8.9±3.4	0.50	0.16
ΔFL at 75% (mm)	11.3±3.3	10.6±2.8	0.60	0.24
ΔFL at 100% (mm)	13.9±4.7	11.5±3.0	0.17	0.62
TF at 25% (N)	148.2±21.8	137.1±19.3	0.23	0.56
TF at 50% (N)	264.0±44.0	234.4±38.4	0.12	0.75
TF at 75% (N)	378.9±67.6	332.5±50.1	0.09	0.80
TF at 100% (N)	495.6±89.7	434.1±66.9	0.09	0.80
Stiffness ($N \cdot mm^{-1}$)	39.5±18.8	39.8±22.7	0.98	0.02

Notes: *d*: Cohen's effect size.

Table 5: Foot and Ankle Outcome Score (FAOS) out of 100 and arch height measures for both low running (LRE) and high running exposure *(*HRE*)* groups (mean±SD).

Variables	**LRE**	**HRE**	***p*-value**	***d***
Pain	98.0±3.4	99.1±1.4	0.54	0.41
Symptoms	96.7±5.2	97.6±4.7	0.69	0.19
Activities of Daily living	99.5±1.0	99.8±0.5	0.32	0.44
Sports & Recreation	99.6±1.4	99.4±1.7	0.84	0.10
Quality of Life	97.9±4.1	93.8±9.4	0.24	0.64
ARCHI	0.32±0.03	0.32±0.13	0.18	0.00

Notes: *: $p<0.05$; *d*: Cohen's effect size; ARCHI: arch height index.

Appendix B: Figures

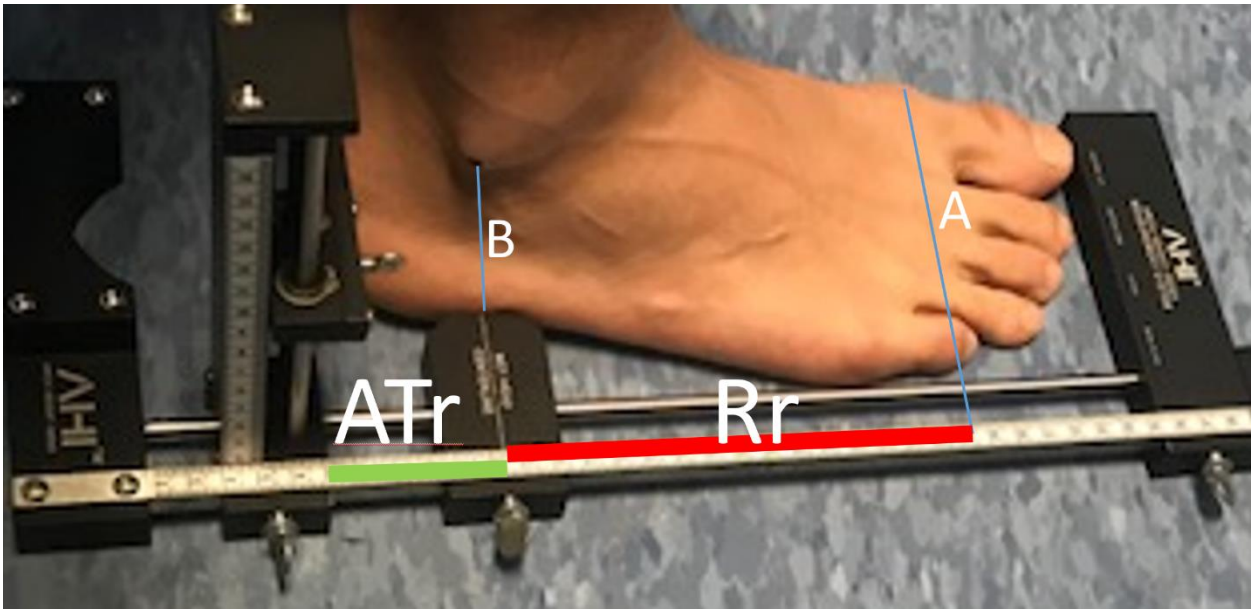

Figure 1: Achilles tendon moment arm (green line; ATr) and resistance moment arm (red line; Rr) where measured using the AHIMS. A) represents the point of the first metatarsal head; which was taken form ARHI measurements prior to this estimation. B) Represents the position of the lateral malleolus (LatMal), which was estimated using a vertical line drawn using a 90-degree angle that was placed flush with the floor prior to foot placement in the AHIMS.

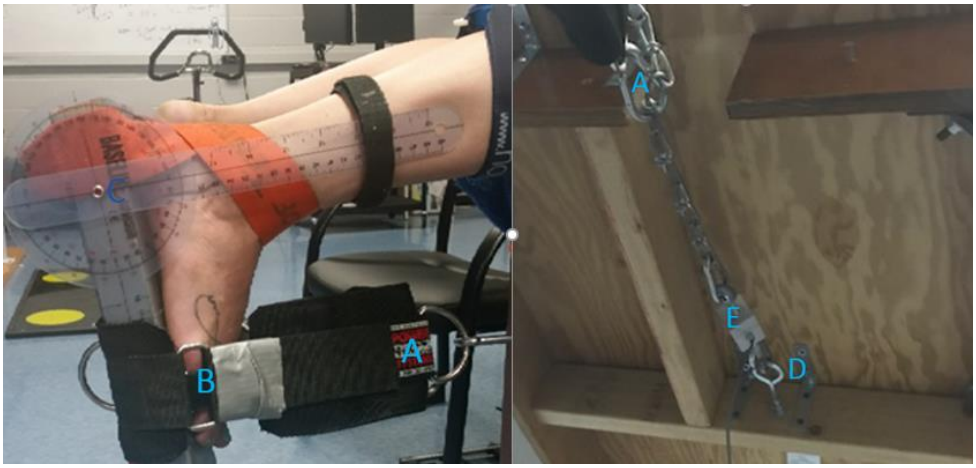

Figure 1: Foot placement on the wooden platform attached to the metal chain in-series with the force transducer. A) Represents the point of chain attachment with the cuff; B) represents the mid-foot (metatarsals) alignment with the cable attached to the force transducer; C) goniometer position used to ensure that the ankle remained within the three-degree position window; D) point of chain attachment to the table, and; E) force transducer attached to chain and table to enable force measurement during contractions.

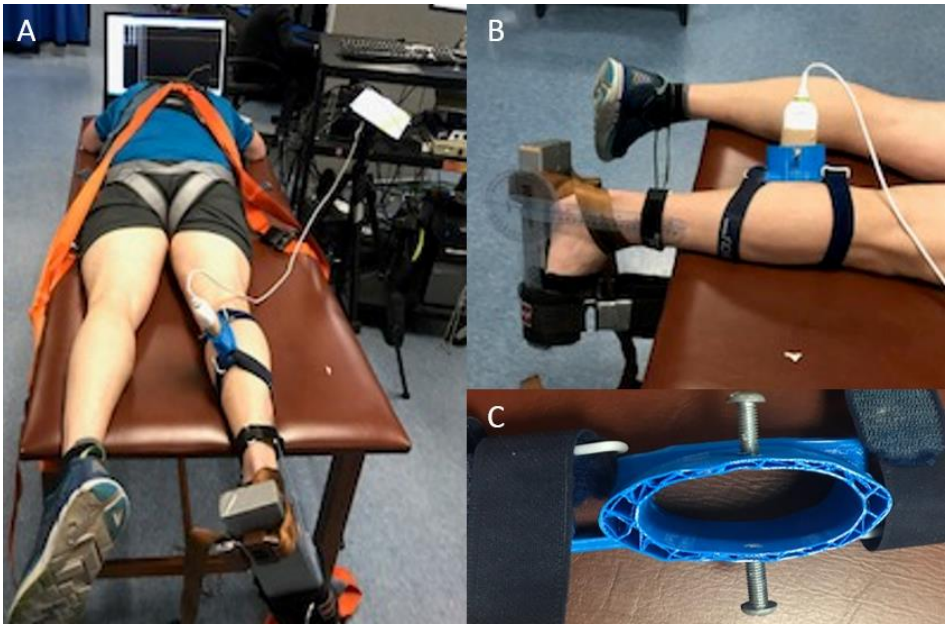

Figure 2: Medial gastrocnemius morphological assessment experimental set up. A) The harness system and safety straps that were used to position and secure the participant to the testing table; B) the ultrasound probe positioning and orientation, and; C) custom-designed plastic mold used to position the probe over the skin above the medial gastrocnemius.

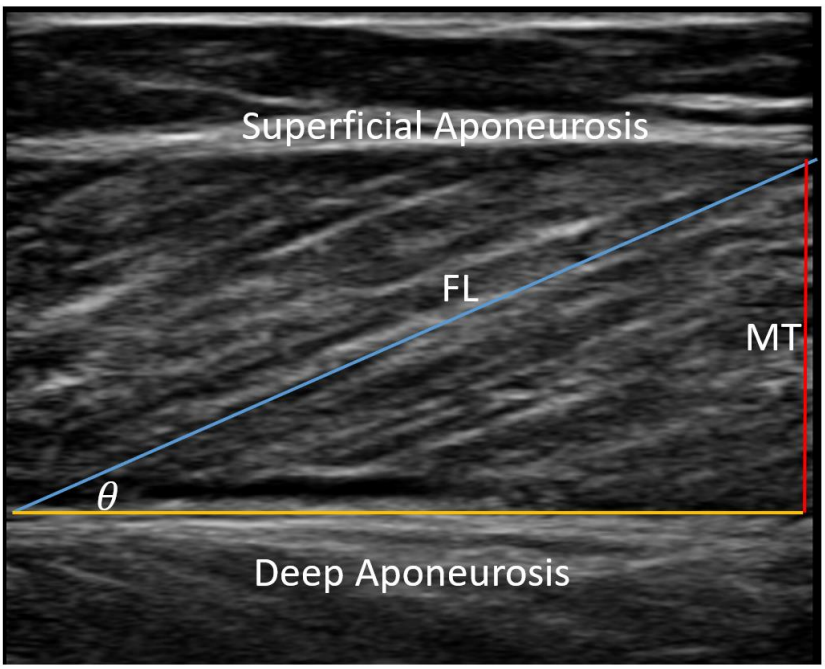

Figure 4: Image measurements of the medial gastrocnemius muscle. NOTE: Fascicle Length (FL) Was calculated using the equation using the following equation FL = MT x Sin θ: where θ is the pennation angles, and MT is muscle thickness.

Appendix C: Consent Form

Consent to Participate in a Research Study

Relationship of lifetime running experience on biomechanics and morphological properties of plantarflexors in older adults

WHY ARE YOU BEING INVITED TO TAKE PART IN THIS RESEARCH?
We are conducting a research study about lifetime running experience in older adults. You are being invited to take part in this research study because you 50+ years old, run at least three times a week, run at least 10 miles per week, and are not currently injured or have had an injury in the past 6 months. If you volunteer to take part in this study, you will be one of about 46 people to do so at the University of Memphis.

WHO IS DOING THE STUDY?
The person in charge of this study is Dr. Max Paquette, an Assistant Professor in the School of Health Studies at the University of Memphis. Ramzi Majaj, a graduate student in the School of Health Studies, will be completing his Master's thesis project with this study. Other graduate students and professors might also be involved with this study.

WHAT IS THE PURPOSE OF THIS STUDY?

By doing this study, we will learn if lifetime running experience affects lower limb movement and muscle characteristics in men and women older runners. We hope to use our results to promote running earlier in life (i.e. promote running in young adult population).

ARE THERE REASONS WHY YOU SHOULD NOT TAKE PART IN THIS STUDY?

The proposed experiment will recruit 46 men and women aged 50 + years who participate in running at least 3 times a week and at least10 miles per week in the last year. Participants will not have any lower body injuries at the time testing and will not have undergone any lower limb surgeries in the past 3 years. If you do not fit these criteria, we apologize but unfortunately, you cannot take part in this study.

WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST?
The research testing will be conducted in the Musculoskeletal Analysis Laboratory (Room 171) at The University of Memphis located in the Elma Roane Field House (next to the main campus track) for one testing session that will last about 90 minutes.

WHAT WILL YOU BE ASKED TO DO?
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. Testing will take place at the University of Memphis Musculoskeletal Analysis Lab (Elma Roane Fieldhouse, room 171). Before testing, you will fill out surveys to make sure you are physically able to participate in the study and to provide us with information regarding your training history.

Your height and mass will be recorded. We will use ultrasound images to take some measurements of your calves while you sit in a chair and perform ankle movements. Following these measurements, reflective markers (plastic spheres covered in reflective tape) will be placed on your body to measure how your legs move when running. You will then perform a 5min warm-up on a treadmill followed by over-ground running and walking trials over the laboratory floor during which we will measure how you run.

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

There are potential risks and discomforts associated with this study. You should not experience any soreness from the testing sessions since you will only be asked to run for 5min at your own pace on the treadmill to warm up and, you will be asked to run over a 25m runway approximately 8 to 10 times at your own pace. Considering your participation in training, this amount of running in your own shoes will not be difficult for you. There is a chance that you could trip on laboratory equipment but the researchers will make sure that you are aware of all equipment positions to avoid any trips or falls. Ultrasound measurements will be performed on your calves. Diagnostic ultrasound is a safe procedure that uses low-power sound waves. There are currently no known risks in humans who are not pregnant. During the testing session, if you feel any discomfort or an injury occurs, the session will be terminated and further communication will determine if the session can be rescheduled.

WILL YOU BENEFIT FROM TAKING PART IN THIS STUDY?

There is no guarantee that you will get any benefit from taking part in this study. However, results from our work may help understand the long term benefits of running to justify running participation at a younger age in order to reduce negative health outcomes later in life.

DO YOU HAVE TO TAKE PART IN THE STUDY?

If you decide to take part in the study, it should be because you really want to volunteer. You will not lose any benefits or rights you would normally have if you choose not to volunteer. You can stop at any time during the study and still keep the benefits and rights you had before volunteering. If you decide not to take part in this study, your decision will have no effect on the quality of care, services, etc., you receive from the University.

IF YOU DON'T WANT TO TAKE PART IN THE STUDY, ARE THERE OTHER CHOICES?

If you do not want to be in the study, there are no other choices except not to take part in the study.

WHAT WILL IT COST YOU TO PARTICIPATE?

There are no costs associated with taking part in the study.

WILL YOU RECEIVE ANY REWARDS FOR TAKING PART IN THIS STUDY?

There is no compensation for the completion of this study.

WHO WILL SEE THE INFORMATION THAT YOU GIVE?

We will make every effort to keep private all research records that identify you to the extent allowed by law. Your information will be combined with information from other people taking part in the study. When we write about the study to share it with other researchers, we will write about the combined information we have gathered. You will not be personally identified in these written materials. We may publish the results of this study; however, we will keep your name and other identifying information private. The information on the forms we will have you fill out will remain private, and only the study staff will see them.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. After you have filled out the necessary forms, they will be kept in a locked file cabinet for which our research team will be the only ones to be able to access them. Any information that gets transferred electronically will be stored on a computer with passcode entry that only the research team will know.

We will keep private all research records that identify you to the extent allowed by law. However, there are some circumstances in which we may have to show your information to other people. If any medical situation arises at which the paramedics or any other form of emergency care have to be called, we may be required to provide health history forms and or contact information. For example, the law may require us to show your information to a court or to tell authorities if you report information that could pose a danger to yourself or someone else. Also, we may be required to show information which identifies you to people who need to be sure we have done the research correctly; these would be people from such organizations as the University of Memphis or any other funding agencies that may have ties with our research study.

CAN YOUR TAKING PART IN THE STUDY END EARLY?

If you decide to take part in the study you still have the right to decide at any time that you no longer want to continue. You will not be treated differently if you decide to stop taking part in the study.

The individuals conducting the study may need to withdraw you from the study. This may occur if you are not able to follow the directions they give you, if they find that your being in the study is more risk than benefit to you, or if the agency funding the study decides to stop the study early for a variety of scientific reasons.

ARE YOU PARTICIPATING OR CAN YOU PARTICIPATE IN ANOTHER RESEARCH STUDY AT THE SAME TIME AS PARTICIPATING IN THIS ONE?

You may not take part in this study if you are currently involved in another research study. It is important to let the investigator/your doctor know if you are in another research study.

WHAT HAPPENS IF YOU GET HURT OR SICK DURING THE STUDY?

If you believe you are hurt or if you get sick because of something that is due to the study, you should call Ramzi Majaj 901-833-0972 immediately. In case of illness or injury during participation in the study, you may reach Ramzi Majaj on his mobile phone at 901-833-0972. You may also reach Dr. Paquette if you have any concerns regarding the study.

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.

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.

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

WHAT IF YOU HAVE QUESTIONS, SUGGESTIONS, CONCERNS, OR COMPLAINTS?

Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions, suggestions, concerns, or complaints about the study, you can contact the investigator, Ramzi Majaj at 901-833-0972, or come by the researcher's office located in Fieldhouse room 369 at The University of Memphis. You can also reach Dr. Max Paquette at 865-310-7820 if you cannot reach Ramzi Majaj. 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. We will give you a signed copy of this consent form to take with you.

WHAT IF NEW INFORMATION IS LEARNED DURING THE STUDY THAT MIGHT AFFECT YOUR DECISION TO PARTICIPATE?

If the researcher learns of new information in regards to this study, and it might change your willingness to stay in this study, the information will be provided to you. You may be asked to sign a new informed consent form if the information is provided to you after you have joined the study.

_____ _____

Signature of person agreeing to take part in the study Date

_____

Printed name of person agreeing to take part in the study

_____ _____

Name of [authorized] person obtaining informed consent Date

Appendix D: IRB Approval

The University of Memphis Institutional Review Board, PRO-FY2017-358, has reviewed and approved your submission in accordance with all applicable statuses and regulations as well as ethical principles.

PI NAME: Ramzi Majaj
CO-PI:
PROJECT TITLE: Impact of lifetime running experience on biomechanics and morphologyical properties of plantarflexors in older adults
FACULTY ADVISOR NAME (if applicable): Maxime Paquette

IRB ID: #3873
APPROVAL DATE: 02/13/2017
EXPIRATION DATE: 03/03/2018
LEVEL OF REVIEW: Expedited
Please Note: Modifications do not extend the expiration of the original approval

Approval of this project is given with the following obligations:

1. If this IRB approval has an expiration date, an approved renewal must be in effect to continue the project prior to that date. If approval is not obtained, the human consent form(s) and recruiting material(s) are no longer valid and any research activities involving human subjects must stop.

2. When the project is finished or terminated, a completion form must be completed and sent to the board.

3. No change may be made in the approved protocol without prior board approval, whether the approved protocol was reviewed at the Exempt, Expedited or Full Board level.

4. Exempt approval are considered to have no expiration date and no further review is necessary unless the protocol needs modification.