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Age, Lower Extremity Muscle Strength, and Running Biomechanics in Healthy Female Recreational Runners

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AGE, LOWER EXTREMITY MUSCLE STRENGTH, AND RUNNING BIOMECHANICS IN HEALTHY FEMALE RECREATIONAL RUNNERS

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ABSTRACT

AGE, LOWER EXTREMITY MUSCLE STRENGTH, AND RUNNING BIOMECHANICS IN HEALTHY FEMALE RECREATIONAL RUNNERS

Heather McConchie Hamilton
Old Dominion University, 2023
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Middle-age and older runners demonstrate differences in running biomechanics compared to younger runners. Females and males demonstrate differences in running biomechanics, and females experience additional hormonal changes with age due to menopause. Despite the biomechanical and physiological differences between females and males, little research has investigated the effect of age specifically in female runners. The overall purpose of this research was to determine the relationships among age, lower extremity muscle strength, and running biomechanics in healthy female recreational runners. Healthy female recreational runners aged 25 – 65 years were recruited. Participants ran on an instrumented treadmill at a training pace and 5K race pace. Isometric and isokinetic lower extremity muscle strength was tested using an isokinetic dynamometer. The first study investigated the relationships between age and running biomechanics at two different running speeds. There was a negative relationship between both training and 5K running speeds and age. There were no significant relationships between age and running kinematic or kinetic variables after controlling for self-selected running speeds. Multiple variables were moderately to very strongly correlated to running speed, including vertical and horizontal ground reaction force, peak hip abduction moment, and peak plantarflexion moment. The second study investigated the relationship between age and isometric and isokinetic strength of the hip abductors, hip extensors, knee extensors, and plantarflexors. There was a negative relationship between age and isometric hip abduction and knee extension strength, but no relationship between age and isometric hip extension and plantarflexion strength or isokinetic strength of the hip extensors, hip abductors, knee extensors, or plantarflexors. Multiple strength variables were weakly to moderately correlated with running speed, including isometric hip abduction, hip extension, knee extension, and plantarflexion. The third study investigated the relationship between age and knee joint stiffness. There was no relationship between age and knee joint stiffness after controlling for self-selected running speed. The research studies from this dissertation reveal that lower extremity muscle strength may play a role in maintaining running speed into middle- and older age. Also, it is clear that running speed is an important factor to consider when investigating the relationship between age and running biomechanics.

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CHAPTER 1

INTRODUCTION AND REVIEW OF THE LITERATURE

1.1 Introduction

Running is a popular form of cardiovascular exercise that provides numerous health benefits (Lavie et al., 2015; D.-C. Lee et al., 2017; Pedisic et al., 2020), including decreased all-cause and cardiovascular mortality (D.-C. Lee et al., 2014). Running is associated with decreased disability and mortality (Chakravarty, Hubert, Lingala, & Fries, 2008), making this an ideal form of physical activity for aging adults. Almost a third (31%) of participants in road races in the Unites States are 45 – 65+ years old (RunningUSA, 2020). However, there are several physiological and biomechanical changes that occur with age that may interfere with older adults’ ability to participate in running (Willy & Paquette, 2019). Additionally, older runners demonstrate differences in running biomechanics compared to younger runners. Because of the remarkable health benefits of running, it is important to understand these changes in running biomechanics to maximize running ability throughout the lifespan. Females experience a unique aging process because of the hormonal changes that occur with menopause. Because menopause affects musculoskeletal physiology and 61% of participants in road races are female (RunningUSA, 2020), it is important to understand female-specific factors that may influence running biomechanics.

1.2 Overview of Age-Related Changes in Running Biomechanics

Physiological Changes with Aging

There are many physiological changes that occur with aging that may affect running participation and performance (Table 1). Both muscle atrophy and loss of muscle fibers occur with age (Wilkinson, Piasecki, & Atherton, 2018), contributing to a decrease in muscle mass, muscle strength, and muscle power with increased age (Mitchell et al., 2012; Pasco et al., 2020; Perry, Carville, Smith, Rutherford, & Newham, 2007). Additionally, there is a decrease in Type II muscle fibers (including decreased fiber area and number of fibers) and an increase in fiber area and number of Type I muscle fibers with increased age (W.-S. Lee, Cheung, Qin, Tang, & Leung, 2006). While isometric and concentric muscle strength decline with age, eccentric muscle strength seems to be preserved (Hortobágyi et al., 1995). Changes in muscle structure and function with increased age contribute to decreased physical function in older adults.

Master athletes are not spared from age-related declines in muscle strength and neuromuscular function (J. Piasecki et al., 2021), though regular physical activity can mitigate the effects of aging (Mitchell et al., 2012; Power et al., 2010; Tarpenning, Hamilton-Wessler, Wiswell, & Hawkins, 2004). For example, long-term endurance and powertraining does not prevent age-related loss of muscle size in the vastus lateralis muscle, but it may contribute to reinnervation of denervated fibers and/or axon sprouting (M. Piasecki et al., 2019). Specifically in older endurance-trained master athletes, chronic endurance exercise is not sufficient to prevent age-related loss of muscle strength with increasing age (Mckendry, Breen, Shad, & Greig, 2018). While sprint running seems to mitigate age-related muscle mass and strength decreases in the plantarflexor muscles, endurance running does not demonstrate the same beneficial effects (Stenroth et al., 2016). In aging endurance runners, decreased muscular function may contribute to changes in running biomechanics.

Running Biomechanics and Aging

Middle-age and older runners demonstrate differences in running biomechanics compared to younger runners (Table 1) (Bus, 2003; Devita et al., 2016; Fukuchi & Duarte, 2008). Specifically, older runners demonstrate decreased self-selected running velocity and shortened step length compared to younger runners at preferred paces (Bus, 2003; Devita et al., 2016; Diss, Gittoes, Tong, & Kerwin, 2015). Based on their results from runners ages 23 – 59 years (n = 110, 59 male participants and 51 female participants), Devita et al. (2016) predict a 20% decrease in preferred running speed and stride length by age 80. Even when running at controlled speeds, older male runners demonstrate decreased stride length and increased stride frequency compared to younger runners (Bus, 2003; Fukuchi & Duarte, 2008; Karamanidis & Arampatzis, 2005). These spatiotemporal differences in running biomechanics between older and younger runners may be related to decreased muscle strength in older runners (Karamanidis & Arampatzis, 2005).

Kinematic and kinetic differences in running biomechanics between older and younger runners are primarily observed in distal joints. Older female and male runners (55 – 71 years) demonstrate decreased sagittal plane ankle excursion (calculated as the difference between maximal and minimal joint angles) compared to younger female and male runners (20 – 36 years) (Fukuchi, Stefanyshyn, Stirling, Duarte, & Ferber, 2014). There is a negative relationship between age and peak ankle plantarflexion moment at a self-selected running pace (r = -.32) (Devita et al., 2016). In a study including both endurance trained runners and non-active participants, the older adults (60 – 69 years) demonstrated decreased ankle plantarflexion moment compared to younger adults (ages 21 – 32 years) when running at a controlled running pace (Karamanidis & Arampatzis, 2005). Similarly, in a group of endurance trained male runners at a self-selected race pace, older runners (60 – 68 years) demonstrated 32% decreased ankle joint moment compared to middle-age runners (50 – 54 years) and 42% decreased ankle joint moment compared to younger runners (26 – 32 years) (Diss et al., 2015). Older female and male runners (55 – 71 years) also demonstrate decreased positive ankle work compared to younger female and male runners (ages 20 – 36 years) (Fukuchi et al., 2014). At a controlled running pace, older (55 – 65 years) and elderly (67 – 73 years) male runners demonstrate decreased sagittal plane knee excursion compared to younger runners (20-39 years) (Bus, 2003; Fukuchi & Duarte, 2008). Devita et al. (2016) report a negative correlation between age and peak knee flexion in midstance ($r = -.20$) in their group of mixed-sex runners (23 – 59 years) when running at a self-selected pace. However, a group of mixed-sex older runners (55 – 71 years) did not demonstrate a difference in knee flexion excursion compared to a group of younger mixed-sex runners (20 – 36 years) when running at a controlled pace (Fukuchi et al., 2014). Although Fukuchi et al. (2014) report decreased knee positive work in their group of older runners compared to younger runners, several studies suggest that younger and older runners demonstrate similar knee and hip joint moments (Devita et al., 2016; Diss et al., 2015; Karamanidis & Arampatzis, 2005; Paquette, DeVita, & Williams, 2017). Thus, unlike walking, in which there is a proximal shift of moment distribution with increased age (DeVita & Hortobagyi, 2000), there is not an observed redistribution of lower extremity joint moments in older runners. Considered together, these studies indicate that older runners demonstrate decreased joint excursion and decreased joint moments compared to younger runners, particularly at the ankle.

Older runners demonstrate decreased peak horizontal (propulsion) and vertical ground reaction forces (GRF) compared to younger runners when running at a preferred pace (Bus, 2003; Devita et al., 2016; Diss et al., 2015). The horizontal (propulsion) GRF decreased 31% between ages 20 and 60 years and was predicted to decrease 47% by 80 years (Devita et al., 2016). Even at controlled running speeds, older runners demonstrate decreased peak vertical and propulsive GRF compared to younger runners (Beck et al., 2016; Fukuchi et al., 2014). However, multiple studies report greater maximal loading rates in older runners compared to younger runners when running at a controlled pace, suggesting that aging runners may have decreased shock absorption capabilities (Bus, 2003; Fukuchi et al., 2014; Lilley, Dixon, & Stiles, 2011). The decreased self-selected running velocity that is observed in aging runners may assist with attenuating ground reaction forces due to a loss of shock absorption (Bus, 2003).

Joint stiffness combines kinematic and kinetic variables to represent the resistance of a joint to displacement by torsional force. Knee joint stiffness is an important variable associated with running economy (Tam, Tucker, Santos-Concejero, Prins, & Lamberts, 2019), and too much or too little knee joint stiffness may contribute to running related injuries (Butler, Crowell III, & Davis, 2003; S. P. Messier et al., 2018). Two studies reported decreased knee joint stiffness in older runners compared to younger runners (Diss et al., 2015; Powell & Williams, 2018). Decreased knee joint stiffness in older runners may contribute to a less efficient running gait, possibly leading to the decreased running gait speed observed in older runners.

While several studies report these differences in running biomechanics between younger and older runners, there may be factors that can mitigate these age-related changes. For example, when young and middle-age running groups were matched by training pace, there was not a significant difference in ankle plantarflexor moment between groups (Paquette et al., 2017). Additionally, in a group of mixed-sex older adults, participants who primarily participated in resistance training as their primary mode of exercise demonstrated greater knee power during running compared to older adults who primarily participated in running for exercise (Borgia, Dufek, Radzak, & Freedman Silvernail, 2022). Maintaining a faster training pace and participating in resistance training may lessen the effects of aging on running biomechanics.

It has been hypothesized that some of these age-related changes in running biomechanics, such as decreased lower extremity joint excursion, decreased joint power, and decreased propulsive GRF, can be attributed to physiological changes with age, such as decreased muscle strength and power and decreased tendon capacities (Karamanidis & Arampatzis, 2005). Decreased muscle strength has been observed in older runners. Male and female older runners (55 – 71 years) demonstrate decreased isometric strength in the hip abductors, hip extensors, and ankle plantarflexors compared to younger runners (20 – 36 years) (Fukuchi et al., 2014). In a group of male runners ages 20 – 80 years (n = 75), there was a significant negative relationship between age and isokinetic (60°/ s) strength of the hip extensors (*r* = -.40), hip flexors (*r* = -.61), knee extensors (*r* = -.54), knee flexors (*r* = -.53), dorsiflexors (*r* = -.41), and plantarflexors (*r* = -.49) (Kim & Park, 2022). Additionally, Karamanidis and Arampatzis (2005) report similar plantarflexion and knee extension strength between older male runners and older male non-active participants (60 – 69 years), and together the older participants demonstrate decreased plantarflexion and knee extension strength compared to the younger (male) participants (21 – 32 years). It is possible that the distal changes seen in aging runners (i.e., decreased ankle excursion, decreased ankle power) are related to decreased strength in the plantarflexor muscles with aging (Fukuchi et al., 2014). Concentric ankle power during running is strongly associated with stride length, running velocity, and peak propulsive ground reaction force (Devita et al., 2016), and ankle plantarflexion strength has been correlated to ankle positive work, ground reaction force propulsive peak, and vertical ground reaction force peak (Fukuchi et al., 2014). In order to draw conclusions about the age-related decrease in muscle strength and its possible effect on running biomechanics, it is important to understand the relationship between muscle strength and running biomechanics.

Table 1. Summary of Effects of Aging and Menopause

Physiological Changes with Age	Physiological Changes with Menopause	Changes in Running Biomechanics with Age
Decreased muscle mass *Decreased muscle strength* *Decreased muscle power* *Decreased Type II muscle fibers*	*Decreased muscle mass* *Decreased muscle strength* *Decreased muscle power*	*Decreased self-selected speed* *Decreased stride length* *Decreased ankle and knee joint excursion* *Decreased ankle joint moment* *Decreased vertical and propulsive ground reaction force* *Decreased knee joint stiffness*

1.3 Overview of Running Biomechanics and Muscle Strength

Several important muscle groups contribute to both support and propulsion throughout the running gait cycle. During the push-off phase of running, the plantarflexor muscles are the primary contributors to propulsion (Hamner, Seth, & Delp, 2010), assisted by the gluteus maximus (Sasaki & Neptune, 2006). During the braking phase of running gait, the knee extensors are the primary contributor to support, assisted by the gluteus maximus and gluteus medius (Hamner et al., 2010). The gluteus medius muscle is likely important in frontal plane support during running, as increased hip adduction during running has been prospectively related to developing patellofemoral pain in female runners (Noehren, Hamill, & Davis, 2013). Because of the high demand on the plantarflexor muscle group during running (Kulmala et al., 2016), it has been suggested that training the plantarflexor muscles may mitigate age-related changes in running biomechanics (Devita et al., 2016); yet, few studies evaluate distal lower extremity strength in runners (Fukuchi et al., 2014). Most studies assess isometric strength, but few studies assess isokinetic strength (Baggaley, Noehren, Clasey, Shapiro, & Pohl, 2015; Ford, Taylor-Haas, Genthe, & Hugentobler, 2013). As running requires alternate shortening and lengthening of muscles, it is important to assess the effect of velocity on muscle tension as a measure of dynamic lower extremity function (Mitchell et al., 2012; Winter, 2009). Additionally, there are very limited studies that assess the relationship between muscle strength and running biomechanics in older runners (Fukuchi et al., 2014). Considering that master runners demonstrate more muscular and tendinous injuries than younger runners (McKean, Manson, & Stanish, 2006), assessing muscle function in the aging runner is important.

Muscle Strength and Running Biomechanics in Healthy Runners

Although it has been suggested that decreases in muscle strength with increased age may contribute to changes in running biomechanics with older age, the relationship between muscle strength and running biomechanics is not well understood. In healthy female runners (n = 23, age range = 18 – 50 years, mean age = 27.4 ± 10.0 years), hip abduction strength has been found to be moderately negatively correlated to hip adduction excursion during running ($r = -.405$), and hip external rotation strength moderately negatively correlated to trunk flexion excursion ($r = -.411$) (Hannigan, Osternig, & Chou, 2018). In a group of mixed-sex cross-country runners (male = 14 participants, mean age 20.2 ± 1.2 years; female = 10 participants, mean age = 19.5 ± 1.5 years), increased hip abductor and extensor strength were moderately related to decreased pelvic frontal plane range of motion and trunk rotation range of motion (Ford et al., 2013). Conversely, there was no correlation between isometric hip abduction strength and peak hip adduction or hip adduction excursion during running in a cohort of healthy female recreational runners (n = 25, age range = 18 – 40, mean age = 29.0 ± 6.0 years) (Baggaley et al., 2015), and no correlation between isometric hip abduction, extension, or external rotation strength and hip adduction excursion during running in another group of healthy female recreational runners (n = 29, mean age = 29.9 ± 4.0 years) (Zeitoune et al., 2020). Similarly, hip abduction strength was not correlated with peak hip adduction angle and hip external rotation strength was not correlated with peak hip internal rotation during running in a group of female runners (combined population of experienced runners, n = 19, mean age = 23.0 ± 3.0 years, and novice runners, n = 19, mean age = 24.0 ± 3.0 years) (Schmitz, Russo, Edwards, & Noehren, 2014). In the same study, side-plank endurance and peak hip internal rotation were weakly negatively correlated (Schmitz et al., 2014). In a group of mixed-sex collegiate distance runners (n = 36, mean age = 20.0 ± 1.5 years), there were no correlations between maximal isometric knee or hip extension strength and hip and knee biomechanics, though there was a weak positive correlation between 1-repetition maximum back-squat strength and peak knee flexion angle (Moffit, Montgomery, Lockie, & Pamukoff, 2020). Older runners (22 male participants and 13 female participants, ages 55 – 71 years) demonstrate decreased isometric hip abduction, hip extension, and plantar flexion strength compared to younger runners (21 male participants and 14 female participants, ages 20 – 36 years), and across both groups of runners, plantar flexion strength was weakly positively correlated with ankle positive work, GRF propulsion peak, and vertical active GRF peak (Fukuchi et al., 2014). In a randomized control trial with older runners (ages 55 – 75 years were recruited, sex not specified), the effects of an 8-week lower extremity strengthening program (n = 33, mean age = 59.8 ± 4.7 years) and flexibility program (n = 31, mean age = 59.8 ± 4.0 years; control group n = 27, mean age = 59.9 ± 3.6 years) on muscle strength and running biomechanics were investigated (Fukuchi, Stefanyshyn, Stirling, & Ferber, 2016). While there were main effects for time (pre- and post-intervention) for both muscle strength and running biomechanics, there were no group effects; that is, both the strengthening and flexibility groups demonstrated changes post-intervention (Fukuchi et al., 2016). Participants demonstrated increased plantarflexion strength and decreased hip extensor strength, but no change in hip abduction strength, and participants demonstrated increased sagittal plane ankle excursion and transverse plane thorax/pelvis excursion and decreased propulsive GRF peak post-intervention (Fukuchi et al., 2016). The authors conclude that the changes in muscle strength and running biomechanics observed post-intervention were not related to the specific training interventions, and they suggest that the training interventions may not have been “strenuous enough” to facilitate change (Fukuchi et al., 2016). The runners’ baseline muscle strength and running biomechanics and experience with strength training may affect their response to a resistance training intervention (Vannatta, Heinert, & Kernozek, 2021). Additionally, because of the cyclic and dynamic nature of distance running, there are likely several factors in addition to muscle strength that contribute to muscle function during running, such as motor control and muscle activation patterns, joint and muscle mobility, muscle endurance, and rate of force development (Hannigan et al., 2018; Moffit et al., 2020). Optimizing all aspects of muscle function can promote improved efficiency during running by allowing the muscle to activate at a decreased percentage of maximal capacity.

Benefits of Resistance Training in Runners and Aging Adults

There are several benefits to resistance training in both runners and aging adults. For runners, greater muscle strength may increase tissue capacity to withstand high loads during running. Additionally, increased lower extremity muscle strength is related to greater leg stiffness (Chen et al., 2022), which is related to improved running economy (Barnes, McGuigan, & Kilding, 2014). Resistance training improves peak running speed, running economy, time to exhaustion at maximal aerobic speed, running speed at maximal oxygen uptake, and increases leg stiffness (Barnes, Hopkins, McGuigan, Northuis, & Kilding, 2013; Beattie, Carson, Lyons, Rossiter, & Kenny, 2017; Johnston, Quinn, Kertzer, & Vroman, 1997; Støren, Helgerud, Støa, & Hoff, 2008). In a study of master runners, a maximal strength training group (4 male and 2 female participants, mean age = 44.2 ± 3.9 years), but not a resistance training group (3 male and 2 female participants, mean age = 44.8 ± 4.4 years) or control group (5 male participants, mean age = 43.2 ± 7.9 years) demonstrated improved running economy at marathon pace after a 6-week training program (Piacentini et al., 2013). Because there were no changes in resting metabolic rate or fat free mass post-intervention, the authors suggest that the improvements in strength are related to neural adaptations, e.g., changes in motor unit recruitment (Piacentini et al., 2013). Isometric strength training of the knee extensors results in increased patellar tendon stiffness and increased rate of torque development (Kubo, Kanehisa, Ito, & Fukunaga, 2001). There are likely several mechanisms by which greater lower extremity muscle strength provides improved efficiency of energy storage and release during running, including increased musculotendinous stiffness, coordination of motor unit recruitment, and increased rate of force development. Although resistance training and muscle strength have not consistently been correlated with running performance (Dellagrana et al., 2015; Kelly, Burnett, & Newton, 2008; Vikmoen et al., 2016), increased muscle strength may assist with mitigating injury risk (Mahieu, Witvrouw, Stevens, Van Tiggelen, & Roget, 2006; Schnackenburg, Macdonald, Ferber, Wiley, & Boyd, 2011) and improving running economy (Quinn, Manley, Aziz, Padham, & MacKenzie, 2011).

Regardless of the relationship between muscle strength and running performance, muscle strength and power are important for healthy aging and preventing disability into older age (Mitchell et al., 2012). In older adults, increased quadriceps strength is associated with decreased mortality (Newman et al., 2006). Resistance training can combat several age-related factors that can negatively affect health: muscle strength, body composition, bone mineral density, and physical function (Baker, Syed-Abdul, Weitzel, & Ball, 2021; Marcos-Pardo et al., 2019; Souza, Barbalho, Ramirez-Campillo, Martins, & Gentil, 2020). Endurance training alone does not preserve muscle mass to the same extent that power training does (Mckendry et al., 2018), so it is important for longevity and physical function to include resistance and power training for older adults, even if they consistently participate in endurance activities.

1.4 Overview of Female-Specific Factors Related to Running

There are specific biomechanical and physiological considerations for female athletes compared to male athletes; however, few studies (6%) in the sports medicine and exercise science literature include only female participants (Cowley, Olenick, McNulty, & Ross, 2021). As discussed previously, increased age is associated with decreased physical performance. In females, there is evidence of an accelerated decrease in performance during middle-age compared to males (Phillips, Rook, Siddle, Bruce, & Woledge, 1993; Ransdell, Vener, & Huberty, 2009; Samson, 2000; Tanaka & Seals, 2008), possibly related to the sex-specific hormonal changes that occur with age.

Biomechanics

Female runners demonstrate unique running biomechanics compared to male runners. Female runners generally demonstrate greater transverse plane and frontal plane hip motion and decreased sagittal plane knee motion compared to male runners (Chumanov, Wall-Scheffler, & Heiderscheit, 2008; Ferber, McClay Davis, & Williams III, 2003; Phinyomark, Hettinga, Osis, & Ferber, 2014). Specifically, Ferber et al. (2003) studied 20 males and 20 females (ages 18 – 45 years) and reported that female runners exhibit greater peak hip adduction and internal rotation angles and peak knee abduction angle during stance compared to the male runners. Additionally, the female participants exhibited greater hip frontal and transverse plane negative work compared to the male runners, suggesting a higher eccentric demand on the hip abductor and hip external rotator muscles in females (Ferber et al., 2003). Similarly, Chumanov et al. (2008) studied 17 male and 17 female healthy participants running at 3 different speeds and 3 different inclinations. The authors reported that the female runners demonstrated greater peak hip adduction and internal rotation angles and hip adduction excursion in stance compared to the male runners across all speeds and inclinations (Chumanov et al., 2008). The female runners also demonstrated greater gluteus maximus activity throughout the running cycle across all speeds, and the female runners demonstrated a greater increase in gluteus medius activity with increased speed compared to the male runners (Chumanov et al., 2008). The support for sex-based analyses in running mechanics has been repeatedly proposed in the literature (Boyer, Freedman Silvernail, & Hamill, 2017; Ferber et al., 2003; Phinyomark et al., 2014), though the studies evaluating the relationship between age and running biomechanics primarily include only male participants (Bus, 2003; Fukuchi & Duarte, 2008; Karamanidis & Arampatzis, 2005), or a combination of male and female participants (Devita et al., 2016; Fukuchi et al., 2014).

Menopause

In addition to biomechanical differences in female runners compared to male runners, females also experience a unique aging process. Compared to males who have a linear decline of testosterone with aging (Decaroli & Rochira, 2017), females experience a steep decline in estrogen production around the time of menopause. A female completes the menopausal transition and enters postmenopause following the final menstrual period (Harlow et al., 2012). The average age of menopause is between 46 and 52 years of age (Schoenaker, Jackson, Rowlands, & Mishra, 2014; Sarianna Sipilä et al., 2020). As females are increasingly participating in running events (Nesburg, Mason, Fitzsimmons, & Hunter, 2023), females may spend a number of years in a postmenopausal phase while participating in running events.

Estrogens have a positive effect on multiple tissues within the body, and therefore multiple systems are affected during menopause (Wend, Wend, & Krum, 2012). 17β-estradiol (E2), is the most potent form of estrogen (Geraci et al., 2021). The marked decrease in E2 production postmenopause can have significant negative effects on musculoskeletal health for the female athlete. Estrogen receptors are present in both skeletal muscle and tendon, suggesting that changes in hormonal concentrations can affect these tissues (S. Sipilä, Finni, & Kovanen, 2015). E2 has a beneficial effect on muscular function through several pathways, including proliferation of muscle satellite cells, preservation of muscle mass, and generation of muscle force (Collins, Laakkonen, & Lowe, 2019; Enns & Tiidus, 2010; Geraci et al., 2021); therefore, the lack of estrogen that occurs postmenopause can affect both skeletal muscle mass and the quality of muscle contraction (Collins et al., 2019). Menopause is associated with decreased lean muscle mass, decreased muscle strength, decreased muscle power, and increased fat mass (Table 1) (Bondarev et al., 2018; V. Messier et al., 2011; S. Sipilä et al., 2015; Sowers et al., 2007; Sternfeld, Bhat, Wang, Sharp, & Quesenberry, 2005). Postmenopausal women have lower strength and lower muscle power than premenopausal women, and a decline in muscle strength in middle-aged women is greater in postmenopausal women than in pre- or perimenopausal women (Bondarev et al., 2018). Menopause is also associated with an increased risk of musculoskeletal injury (Enns & Tiidus, 2010). Both male and female master athletes demonstrate evidence of motor unit remodeling with increased age, likely to minimize loss of muscle fibers; however, aging females were found to have slower motor unit firing rates, which suggests that females may be more likely to develop a slower muscle phenotype with age (J. Piasecki et al., 2021). Women's world-record performances decline faster that men's performance after the age of 55 years in endurance events, particularly in running (Ransdell et al., 2009).

The Gap in Knowledge

Physical activity has been shown to be beneficial to muscle strength and muscle mass in menopausal women (Bondarev et al., 2018; Sarianna Sipilä et al., 2020), but this effect has not been studied specifically in menopausal female runners. There is a particular need for further investigation of female master athletes (Mckendry et al., 2018). The female aging process may contribute to changes in musculoskeletal physiology that can affect running biomechanics. Again, this highlights the need to consider sex-specific analyses in the study of running biomechanics, especially when studying the effects of age.

Both increased age and female sex are risk factors for running-related injury (McKean et al., 2006; S. P. Messier et al., 2018; Nielsen et al., 2013; Taunton et al., 2003). However, few studies have explored aging-related biomechanics specifically in female runners. Lilley et al. (2011) measured ground reaction forces and knee and ankle biomechanics of 15 middle-age (40 – 60 years) and 15 young (18 – 24 years) female runners at a controlled pace of 3.5 m/s. The middle-aged runners demonstrated a greater vertical loading rate, peak ankle eversion angle, peak knee internal rotation angle, and peak knee external adductor moment compared to the younger runners (Lilley et al., 2011). Because these biomechanical variables have been associated with osteoarthritis and injury, the authors suggest that the older female runners may have a higher risk of experiencing these musculoskeletal conditions (Lilley et al., 2011). However, sagittal plane kinematics and kinetics were not reported in this study. Hamilton and Kakar (2022) studied a group of female runners (n = 46, 18 – 65 years) running at a self-selected jogging (mean 2.66 ± .30 m/s) and maximal (mean 3.80 ± .61 m/s) pace. There were negative relationships between age and peak eversion, dorsiflexion, and knee flexion, and hip adduction at initial contact at both running paces (Hamilton & Kakar, 2022). However, ground reaction forces were not collected in this study, and the addition of kinetic variables would provide further information about running biomechanics in aging female runners. In a study including a group of young female runners (n = 6, 20 – 39 ages), older female runners (n = 6, 60 – 74 years), young male runners (n = 13, 20 – 39 years), and older male runners (n = 16, 60 – 74 years), there were no interactions between sex and age for the variables reported, including maximum vertical GRF and vertical loading rate (Kline & Williams III, 2015). However, there were relatively few running variables reported and there was a small sample size of female runners. Because of the unique differences in both running biomechanics and aging in female runners compared to male runners, it is important to understand running biomechanics specifically in this population to develop training and rehabilitation programs for master female runners.

1.5 Statement of the Problem

Although differences in running biomechanics between younger and middle-age and older runners have been well-established, few studies have explored age-related changes in biomechanics specifically in female runners (Hamilton & Kakar, 2022; Lilley et al., 2011). Because of the unique differences in running biomechanics and aging in female runners compared to male runners, it is important to understand running biomechanics in this population to develop training and rehabilitation programs specifically for the master female runner. Additionally, most studies investigating the effect of age on running biomechanics compare a younger cohort to a middle-age or older cohort and do not consider age as a linear variable. Because of the gradual physiological changes that occur with age, it is possible that running biomechanics are progressively changing throughout middle- and into older age.

1.6 General Purpose of the Dissertation

The overall purpose of this dissertation is to determine the relationships among age, lower extremity muscle strength, and running biomechanics specifically in healthy female recreational runners.

1.7 Specific Aims and Hypotheses

Experiment one

Aim 1.1: Determine the relationship between age (across the continuum) and lower extremity running biomechanics in female recreational runners at two different self-selected paces: an “easy” training pace and a 5K race pace.

> Hypothesis 1.1: There will be a negative correlation between age and ankle and knee joint excursion and peak ankle joint moment for the 5K race pace, but not for the easy training pace.

Aim 1.2: Determine the relationship between age and body mass index (BMI), training pace, 5K pace, and weekly running mileage.

> Hypothesis 1.2: There will be a negative relationship between age and training pace and 5K race pace, but no relationship between age and BMI or weekly running mileage.

Experiment two

Aim 2.1: Determine if there is a relationship between age and lower extremity muscle strength in female recreational runners.

> Hypothesis 2.1: There will be a negative relationship between age and isometric and concentric strength, but no relationship between age and eccentric strength.

Aim 2.2: Determine if there is a relationship between lower extremity muscle strength and self-selected running pace.

Hypothesis 2.2: There will be a positive relationship between lower extremity muscle strength and self-selected running pace.

Experiment three

Aim 3.1: Determine if there is a relationship between age and knee joint stiffness in female recreational runners.

Hypothesis 3.1: There will be a negative relationship between age and knee joint stiffness.

Aim 3.2: Determine if there is a relationship between knee joint stiffness and knee extension strength in female recreational runners.

Hypothesis 3.2: There will be a positive relationship between knee joint stiffness and knee extension strength.

CHAPTER 2

AGELESS RUNNING: SPEED, NOT AGE, IS RELATED TO RUNNING BIOMECHANICS IN FEMALE RECREATIONAL RUNNERS

2.1 Introduction

Running is a popular form of aerobic physical activity that provides numerous health benefits (Lavie et al., 2015; D.-C. Lee et al., 2017; Pedisic et al., 2020), including decreased all-cause and cardiovascular mortality and decreased disability (Chakravarty et al., 2008; D.-C. Lee et al., 2014). Because of the many health benefits of running, this may be an ideal form of physical activity for aging adults. However, there are several factors that may interfere with older adults' ability to participate in running, including lifestyle factors and physiological and biomechanical changes with age (Willy & Paquette, 2019). In addition to the effects of aging, middle-age and older female runners experience the hormonal effects of menopause, which may create additional challenges to maintaining running volume and intensity.

Older runners demonstrate differences in running biomechanics compared to younger runners, including decreased preferred running pace, decreased stride length, increased stance time, and decreased propulsive ground reaction force (Bus, 2003; Devita et al., 2016; Diss et al., 2015; Fukuchi & Duarte, 2008; Fukuchi et al., 2014). Biomechanical changes in running mechanics of older runners are primarily observed in distal joints. Older runners demonstrate decreased sagittal plane ankle and knee joint excursion (Bus, 2003; Fukuchi & Duarte, 2008; Fukuchi et al., 2014) and decreased plantarflexion moments (Devita et al., 2016) compared to younger runners. However, younger and older runners demonstrate similar knee and hip joint moments (Devita et al., 2016; Diss et al., 2015; Paquette et al., 2017).

Most studies investigating the relationship between age and running biomechanics compare a group of younger runners to a group of older runners and do not consider age as a linear variable. However, increased age is associated with decreased muscle mass, decreased muscle strength (2 – 4% per year on average), decreased muscle power, decreased number and slower firing rate of motor units, and decreased maximal oxygen consumption (Hawkins, Marcell, Jaque, & Wiswell, 2001; Janssen, Heymsfield, Wang, & Ross, 2000; Mitchell et al., 2012; M. Piasecki et al., 2016), possibly contributing to linear changes in running biomechanical variables with increased age. In one of the few running studies considering age as a continuous variable, Devita et al. (2016) reported inverse linear relationships with age and self-selected running velocity, stride length, peak vertical and propulsive ground reaction force, and peak ankle power. There are likely subtle, progressive changes that begin in middle age that contribute to the differences in biomechanics observed between older and younger runners.

There are several important muscle groups contributing to supporting and propelling the body during running. The plantarflexor muscles are the primary contributors to propulsion during the push-off phase of running gait (Hamner et al., 2010). Also contributing to propulsion is the gluteus maximus (Sasaki & Neptune, 2006). The knee extensor muscles are the primary contributor to support during the braking phase of running gait (Hamner et al., 2010). The gluteus maximus and gluteus medius also contribute to support in the stance phase of gait (Hamner et al., 2010; Sasaki & Neptune, 2006). Increased hip adduction during running has been prospectively related to developing patellofemoral pain in female runners (Noehren et al., 2013), suggesting the gluteus medius muscle is important in frontal plane support during running. Investigating the kinematics and kinetics associated with these muscle groups in aging runners can provide insight into how these contributions may change with age.

In addition to physiological aging, females experience the unique hormonal experience of menopause in middle-age. The final menstrual period marks the end of the menopausal transition (Harlow et al., 2012), and menopause is associated with a steep decline in estrogen production. Estrogen has a positive effect on several systems within the body; therefore, multiple systems may be negatively affected during menopause (Wend et al., 2012). Menopause is associated with decreased lean muscle mass, decreased muscle strength, decreased muscle power, increased fat mass, and increased risk of musculoskeletal injury (Bondarev et al., 2018; Enns & Tiidus, 2010; V. Messier et al., 2011; S. Sipilä et al., 2015; Sowers et al., 2007; Sternfeld et al., 2005). These changes associated with menopause may contribute to disadvantageous changes in running biomechanics in aging female runners. Because of the differences in aging processes, in addition to the differences in running biomechanics between males and females (Chumanov et al., 2008; Ferber et al., 2003), it is imperative that research examines the effects of aging on running biomechanics in female athletes.

Understanding age-related changes in running biomechanics is important for designing rehabilitation and training programs for the aging female runner. The purpose of this study is to determine the relationship between age (across the continuum) and running biomechanics in female recreational runners at two different self-selected paces: an “easy” training pace and a 5K race pace. Runners spend most of their running volume at a training pace that is relatively slower than their racing pace; however, a greater running speed places a greater demand on the musculoskeletal system and may expose differences in running biomechanics not observed at lower intensities. We hypothesize that there will be a negative correlation between age and ankle and knee joint excursion and peak ankle joint moment for the 5K race pace, but not for the easy training pace. A secondary purpose of the study was to determine if there is a relationship between age and body mass index (BMI), training pace, 5K pace, and weekly running distance. We hypothesize that there will be a negative relationship between age and training and 5K pace (as age increases, pace becomes slower), but no relationship between age and BMI or weekly running distance.

2.2 Methods

This study was approved by the Old Dominion University Institutional Review Board. Fifty-two female recreational runners were recruited from the local running community through social media and word-of-mouth. Inclusion criteria were as follows: ages 25 – 65 years old, running at least 10 miles (16 km) per week on average for at least the past 6 months with the shortest run of the week at least 3 miles, and comfortable running on a treadmill. Participants were excluded if they had any lower extremity injury or surgery in the past 6 months that would have any negative effect on training (Yamato, Saragiotto, & Lopes, 2015), musculoskeletal pain affecting running mechanics, currently pregnant, or less than 1 year postpartum. Participants were educated on the purpose of the study and signed an informed consent document prior to participation. Participants were asked to avoid intense exercise 48 hours prior to data collection. Leg dominance was determined by asking participants with which limb they would kick a soccer ball (Wilkerson et al., 2004). Participants wore their own running shoes. A priori power analyses determined at least 51 participants would be required for an alpha level of .05 and 80% power (G*Power 3.1) using a previous study reporting a negative relationship between age and maximum propelling ground reaction force during running (r = -.383, Devita et al., 2015).

After measuring height (m) and body mass (kg), twenty-nine reflective markers were attached following anatomical landmarks using double-sided tape (Figure 1): bilateral anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), iliac crests, medial and lateral femoral epicondyles, lateral & medial malleoli, heel, and first, second, and fifth metatarsal heads, spinous process of C7, spinous process of T10, manubrium, xiphoid, bilateral acromion, and right scapula. Thigh and shank clusters (4 markers each) were also placed bilaterally. The medial ankle and medial knee markers were removed following the calibration trial; the remaining markers (including the clusters) were used for segment tracking. Kinematics were collected using a 9-camera motion capture system (Vicon Nexus 2.10, 100 Hz) and a split-belt instrumented treadmill (Motek Medical, Netherlands, 1000 Hz).

Following the static calibration trial, the participants ran for 5 minutes at their self-selected warm-up pace for treadmill familiarization. Next, the participants ran for 5 minutes at their self-selected "easy" training pace (JOG), which was described to participants as a comfortable pace that they could easily sustain while holding a conversation (Agresta, Peacock, Housner, Zernicke, & Zendler, 2018; Hannigan et al., 2018). Finally, the participants ran for 5 minutes at their self-selected 5K pace (RUN), which was described to the participants as a pace that is challenging but that could be sustained for at least 20 minutes as if running a 5K race. Data were collected for 30 seconds during the fourth and fifth minute for JOG and RUN paces. An average of 14 strides was used to calculate variables of running biomechanics.

Data processing. Visual 3D v6 (C-motion, Inc.) was used for data processing. A 6-DOF model was used for the bilateral lower extremities and trunk. The pelvis segment was defined using the bilateral ASIS and PSIS markers, using the Helen Hayes model to define the hip joint center (Davis, Õunpuu, Tyburski, & Gage, 1991). The thigh segment was defined using the hip joint center and the lateral and medial femoral epicondyle markers. The midpoint of the lateral and medial femoral epicondyle markers was used to define the knee joint center, which was used with the lateral and medial malleoli markers to define the shank segment. The ankle joint center was defined as the midpoint between the lateral and medial malleoli markers, and the foot segment was defined using the ankle joint center and the first and fifth metatarsal head markers. The C7, T10, manubrium, and xiphoid markers were used to define the thorax. Kinematic data was interpolated using a least-squares fit of a third order polynomial with a three data point fitting and a maximum gap fill of 10 frames. Kinematic and force plate data were smoothed using a fourth-order Butterworth low-pass filter of 10 Hz (Bisseling & Hof, 2006; Kristianslund, Krosshaug, & Van den Bogert, 2012; Radzak, Putnam, Tamura, Hetzler, & Stickley, 2017). The right-hand rule with a Cardan rotational sequence (Sagittal-Frontal-Transverse) was used for 3D angular calculations. Newtonian and Euler three-dimensional equations of motion were used for inverse dynamics calculations (Winter, 2009); internal joint moments were calculated and normalized to body mass.

Fifteen biomechanical variables were calculated from an average of 14 consecutive steps of the dominant limb for each running pace. Step length (m), cadence (steps/min), stance and swing times (s), peak vertical ground reaction force (vGRF; N/kg), peak propulsive and braking ground reaction force (N/kg), hip extension angle at toe-off, hip adduction, knee flexion, and ankle dorsiflexion/plantarflexion angular excursion during stance, and peak internal hip abduction, hip extension, knee extension, and ankle plantarflexion moments (N/kg). Excursions were calculated as the difference between the angle at initial contact and the peak angle during the stance phase (Hannigan et al., 2018). Initial contact was defined as the first frame the vGRF is ≥ 20 N and toe-off was defined as the first frame the vGRF is < 20 N (Karamanidis, Arampatzis, & Brüggemann, 2006). Of note, 2 participants were excluded from the RUN hip, 2 participants from the RUN knee, and one participant from the JOG spatiotemporal analyses because of collection issues. In addition, one participant was excluded from the JOG analyses because her gait did not include a flight phase.

Figure 1. Marker Placement for Running Biomechanical Analysis.

Statistical analysis. First, a two-way mixed effect model with absolute agreement was used to calculate the intra-class correlation coefficients (ICC) between the joint moments of the fourth and fifth minutes of running at each pace. ICCs indicated excellent agreement (all ICCs > 0.97), confirming participants reached a steady state of running. Next, Pearson's product moment correlation coefficients (*R*) were calculated to determine the relationships between age and BMI, JOG pace, RUN pace, and weekly running distance.

Multiple linear regression was used to determine the relationship between age and biomechanical variables (listed above) from the last minute of both JOG and RUN paces. Running speed was included in the first regression block for all multiple linear regressions to control for self-selected pace. Separate multiple linear regressions were used for each variable and for both JOG and RUN paces. Statistical analysis was performed using IBM SPSS Statistics software (version 27).

Prior to performing regressions, test assumptions (i.e., normal distribution, no outliers, independent errors, and no multicollinearity) were assessed. Histograms and P-P plots were visualized to confirm normality, the Durbin-Watson statistic was used to assess independent errors (values between 1 and 3 were acceptable), and multicollinearity was evaluated by correlations between predictor variables (r less than .9 was acceptable) and the variance inflation factor (VIF) and tolerance statistic (VIF less than 10 and tolerance greater than .1 were acceptable) (Field, 2018). Outliers were identified as values with a standardized residual greater than 3. If an outlier was identified, the analysis was repeated without the variable to confirm that it was not an influential case. Influential cases were excluded from analysis.

2.3 Results

Fifty-two female runners (ages 27 – 65 years) are included in this study. Demographic information and results of the correlation analysis are presented in Table 2. There was a moderate negative relationship between age and JOG ($p < .001$) and RUN ($p = .001$) speed (Figure 2), but no relationship between age and BMI or weekly running distance.

For both JOG and RUN, after controlling for speed, there were no significant relationships between age and running biomechanics variables (Table 3). For JOG, there were very strong correlations between speed and step length and strong correlations between speed and stance time and braking GRF (Table 4). There were moderate correlations between speed and cadence, hip extension at TO, plantarflexion moment, hip abduction moment, vGRF, and propulsive GRF. There were weak correlations between speed and dorsiflexion/plantarflexion excursion and hip extension moment. For RUN, there were very strong correlations between speed and step length and braking GRF (Table 4). There were strong correlations between speed and stance time, plantarflexion moment, and propulsive GRF. There were moderate correlations between speed and cadence, dorsiflexion/plantarflexion excursion, hip extension at TO, hip abduction moment, and vGRF. There were weak correlations between speed and knee flexion excursion, hip adduction excursion, knee extension moment, and hip extension moment.

Table 2. Participant Characteristics and Results of Correlation Analysis with Age.

Participant Characteristics (n = 52)	**M ± SD**	***R***	***p-value***
Age (years)	43.4 ± 8.5	-	-
Body Mass Index (kg/m^2)	23.7 ± 2.6	.1	.499
JOG speed (m/s)	2.6 ± .3	-.49	< .001*
RUN speed (m/s)	3.0 ± .4	-.43	.001*
Weekly running distance (km/week)	37.3 ± 21.2	-.24	.094

*$p < .05$

Figure 1. Correlations Between Running Speed and Age.

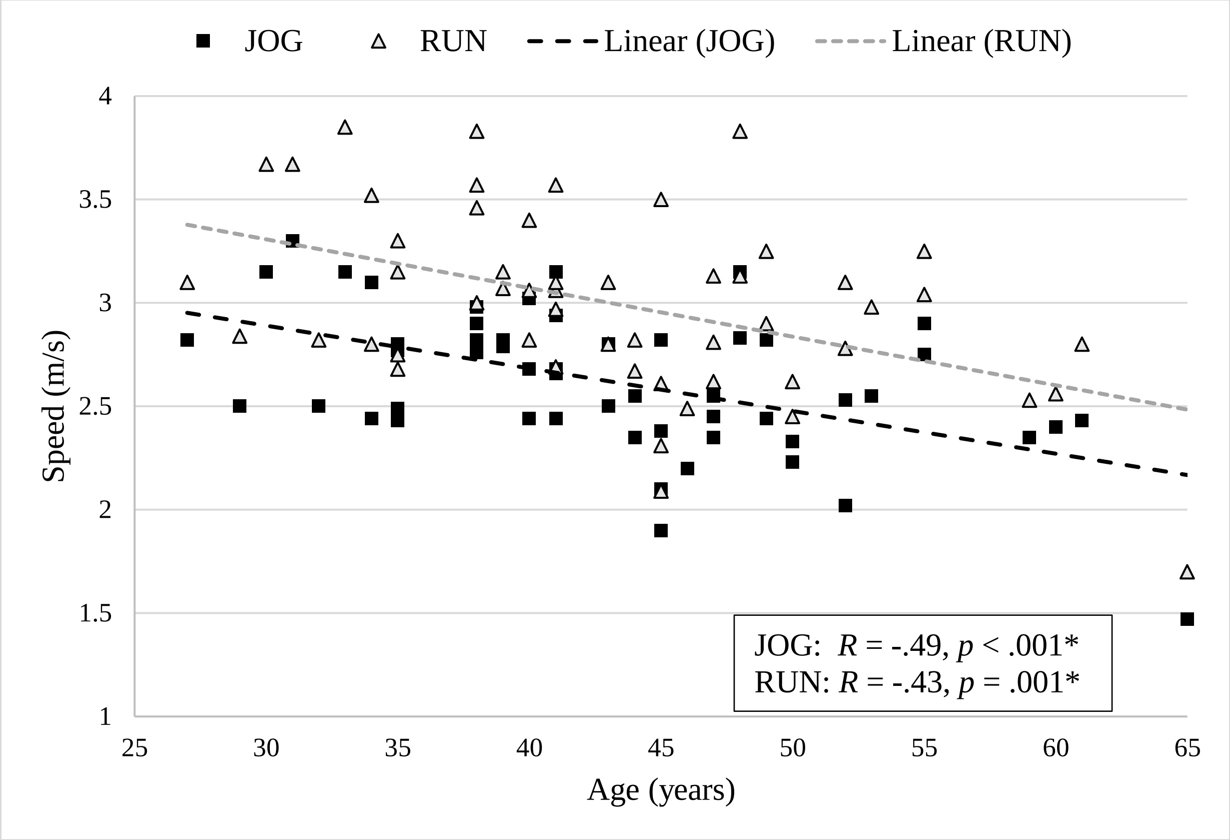


Table 3. Results of Multiple Regression for JOG and RUN Biomechanical Variables.

Variable	**JOG**				**RUN**			
	M ± SD	**β**	**SE**	***p*-value**	M ± SD	**β**	**SE**	***p*-value**
Step length (m)	.93 ± .10	-.001	.001	.381	1.02 ± .13	-.001	.001	.262
Cadence (steps/min)	169.36 ± 10.08	.14	.17	.425	174.65 ± 10.30	.20	.17	.242
Stance time (s)	.29 ± .03	.000	.000	.944	.27 ± .03	.000	.000	.942
Swing time (s)	.42 ± .03	.000	.001	.447	.42 ± .03	-.001	.001	.208
DF/PF excursion (°)	21.29 ±6.42	-.15	.12	.196	22.51 ± 6.49	-.10	.11	.363
KneeFLEX excursion (°)	29.40 ±4.15	.02	.08	.791	29.16 ± 4.81	.01	.08	.871
HipADD excursion (°)	5.86 ±2.83	.02	.06	.717	6.06 ± 2.77	.003	.05	.956
HipEXT TO (°)	8.68 ± 6.14	.08	.11	.481	10.29 ± 6.89	.09	.12	.453
PlantarFLEX mom (N/kg)	1.58 ±.39	-.002	.01	.741	1.66 ± .31	.001	.004	.852
KneeEXT mom (N/kg)	2.99 ±.48	-.01	.01	.198	2.98 ± .44	-.013	.01	.093
HipABD mom (N/kg)	1.41 ± .32	-.001	.01	.885	1.41 ± .34	.003	.01	.608
HipEXT mom (N/kg)	.78 ± .24	-.01	.01	.136	.90 ± .28	-.01	.01	.150
vGRF (N/kg)	21.38 ± 1.83	-.04	.03	.287	21.58 ± 1.96	-.05	.03	.124
PropGRF (N/kg)	2.21 ± .38	.01	.01	.266	2.50 ± .49	.01	.01	.142
BrakGRF (N/kg)	-2.36 ± .31	-.01	.01	.159	-2.57 ± .41	-.01	.01	.061

DF = dorsiflexion, PF = plantarflexion, KneeFLEX = knee flexion, HipADD = hip adduction, HipEXT = hip extension, TO = toe off, PlantarFLEX = plantarflexion, KneeEXT = knee extension, HipABD = hip abduction, vGRF = vertical ground reaction force, PropGRF = propulsion ground reaction force, BrakGRF = braking ground reaction force.

Table 4. Correlations of Running Speed and Variables of Running Biomechanics.

	JOG		**RUN**	
Variable	*r*	*p*-value	*r*	*p*-value
Step length (m)	.81	< .001*	.88	< .001*
Cadence (steps/min)	.50	< .001*	.46	< .001*
Stance time (s)	-.71	< .001*	-.70	< .001*
Swing time (s)	-.02	.441	.06	.331
DF/PF excursion (°)	.35	.006*	.48	< .001*
KneeFLEX excursion (°)	.16	.132	.38	.003*
HipADD excursion (°)	.19	.095	.32	.012*
HipEXT TO (°)	.43	.001*	.48	< .001*
PlantarFLEX mom (N/kg)	.54	<.001*	.67	< .001*
KneeEXT mom (N/kg)	.04	.379	.38	.004*
HipABD mom (N/kg)	.41	.002*	.43	.001*
HipEXT mom (N/kg)	.28	.027*	.27	.029*
vGRF (N/kg)	.41	.002*	.47	< .001*
PropGRF (N/kg)	.76	< .001*	.81	< .001*
BrakGRF (N/kg)	-.56	< .001*	-.73	< .001*

DF = dorsiflexion, PF = plantarflexion, KneeFLEX = knee flexion, HipADD = hip adduction, HipEXT = hip extension, TO = toe off, PlantarFLEX = plantarflexion, KneeEXT = knee extension, HipABD = hip abduction, vGRF = vertical ground reaction force, PropGRF = propulsion ground reaction force, BrakGRF = braking ground reaction force. *****$p < .05$

2.4 Discussion

The purpose of this study was to determine if there is a relationship between age and running biomechanics in female recreational runners. There was a moderate negative relationship between age and JOG and RUN speeds. After controlling for running speed, there were no significant relationships between age and any variables for running biomechanics for either JOG or RUN. The presence of a linear relationship between age and running speed suggests that there may be gradual changes that occur throughout middle-age contributing to the differences in running biomechanics observed between younger and older runners.

These results are consistent with other studies reporting decreased self-selected running pace with increased age as a result of shortened step length (Bus, 2003; Devita et al., 2016; Diss et al., 2015). Using their data from participants aged 23 to 59 years, Devita et al. (2016) predicted .33% reduction in training pace per year from age 20 to age 80 in a mixed-sex group of runners. Similarly, our results suggest a .32% reduction in training pace and .28% reduction in 5K pace per year from age 25 to 60 years. The average running pace of the participants in the Devita et al. (2016) study, including mixed-sex runners ages 23 – 59 years (59 males, 51 females), was 3.00 ± .35 m/s, almost identical to the average 5K pace in the current study, 3.0 ± .4 m/s. Despite the physiological differences in aging between males and females, the decline in running pace with increased age, at least up until the seventh decade, is likely similar between males and females. Decreased walking gait speed is a strong predictor of mortality in older adults (Franklin, Brinks, Sacks, Trivax, & Friedman, 2015) and is associated with decreased maximal aerobic capacity, decreased lower extremity muscle strength, decreased reaction time, and decreased balance (Fiser et al., 2010; Tiedemann, Sherrington, & Lord, 2005). It is likely that the same physiological processes contributing to decreased walking speed play a role in the slowing of running velocity in older adults.

While there were no significant relationships between age and running biomechanics after controlling for self-selected running speed, several of the running biomechanical variables were moderately to strongly correlated with running speed. Generally, lower extremity joint angles and torques, GRF, and stride length all increase with increased recreational running speed (Fukuchi, Fukuchi, & Duarte, 2017; Orendurff et al., 2018). In the current study, there were positive correlations between speed and lower extremity joint excursions and moments at both the JOG and RUN paces. Orendurff et al. (2018) studied recreational runners running at 85%, 100%, 115% and 130% of their self-selected pace and reported increased peak hip extension angle, peak knee extensor moment in stance, and peak plantarflexion angle and moment with increased running speed. The authors note that there was a greater increase in peak power generation at the ankle compared to the hip or knee with increasing speed, suggesting that the ankle is an important contributor to lower extremity biomechanics (Orendurff et al., 2018). In the current study, there was a moderate correlation between speed and plantarflexion moment at the JOG pace and a strong correlation at the RUN pace, which agrees with the postulation that the ankle plays an important role in lower extremity running biomechanics.

If increased recreational running speeds are associated with greater joint excursions and moments, it is plausible that changes in running biomechanics observed in aging runners are primarily related to decreased running speed, as opposed to related solely to increased age. However, several studies report differences in running biomechanics between younger and older runners at controlled running speeds. Bus (2003) studied a group of younger (20 – 35 years) and older (55 – 65 years) well-trained male runners at both a self-selected and a controlled running speed (3.3 m/s) and reported that at both speeds, older runners demonstrated shorter stride lengths and higher stride rates. Additionally, the older runners demonstrated decreased knee and ankle ROM and a higher maximal initial loading rate and impact peak force compared to the younger runners at the controlled running speed, suggesting a “decrease in the shock-absorbing capacity of the musculoskeletal system in the older runners” (Bus, 2003). Lilley et al. (2011) also reported greater loading rates in a group of middle-age female runners (n = 15, 40 – 60 years) compared to young female runners (n = 15, 18 – 24 years) when running at a controlled pace (3.5

m/s). Because of the decreased stride length that older runners demonstrate, the older runners would accumulate a greater number of steps at a given distance compared to younger runners; thus, it may be important for older runners to use alternative methods of tracking training load instead of weekly mileage (Bus, 2003; Paquette, Napier, Willy, & Stellingwerff, 2020). Fukuchi et al. (2014) compared a mixed-sex group of younger (20 – 36 years, 21 males, 14 females) and older (55 – 71 years, 22 males, 13 females) recreational runners at a controlled running speed (2.7 m/s) and reported that the older runners demonstrated decreased dorsiflexion – plantarflexion and hip adduction – abduction excursion, increased maximal loading rate, decreased knee and ankle positive work, and decreased propulsive and active vertical GRF compared to the younger runners. In female runners (n = 46, 18 – 65 years), age has been negatively correlated with peak eversion, peak knee flexion, peak dorsiflexion, and hip adduction at initial contact after statistically controlling for self-selected running pace (Hamilton & Kakar, 2022), suggesting an influence of increased age on running biomechanics specifically in female runners. Karamanidis and Arampatzis (2005) studied younger (21 – 32 years) and older (60 – 69 years) males running at a controlled pace (2.7 m/s) and found that the older participants demonstrated shorter step length, increased stance time, decreased flight time, and decreased maximal ankle plantarflexion moment compared to the younger participants. The authors suggest that the older runners adopt this modified running gait to increase safety and to adapt to the reduced plantar flexor and knee extensor musculotendinous capacities (Karamanidis & Arampatzis, 2005). Taken together, these studies provide potential reasons for decreased self-selected running speeds in older runners, that is, older runners adopt a slower running speed as a strategy to mitigate impact forces and loading rates and to work within their available musculotendinous abilities. However, it is likely that these biomechanical changes are occurring gradually throughout middle age; therefore, it is important to account for age as a linear variable, not simply a dichotomous variable, when training or rehabilitating aging runners (Devita et al., 2016).

Training intensity (i.e., running speed) may help protect against age-related changes in running biomechanics. When younger runners (mean age = 30 years) were matched with middle-aged runners (mean age = 58 years) for training pace (young = 2.9 m/s, middle age = 2.8 m/s), there were no differences in lower extremity joint kinetics between groups when running at a controlled speed of 2.7 m/s (Paquette et al., 2017). The authors do note an 8.3% lower peak propulsive GRF in the middle-aged runners compared to the younger runners (Paquette et al., 2017). There were strong correlations between speed and propulsive GRF at the JOG and at the RUN pace. Even if not directly related with age, runners at slower paces demonstrate decreased propulsive GRF. In a 40-year age range of runners, peak propulsive GRF reduced by .70% per year (Devita et al., 2016). Maximum propelling GRF is directly associated with maximum positive ankle power (Devita et al., 2016), and plantar flexor muscle function decreases with age (Karamanidis & Arampatzis, 2005). Several authors highlight the importance of training the plantarflexor musculotendinous complex for aging runners (Devita et al., 2016; Fukuchi et al., 2014; Willy & Paquette, 2019). During running and walking, the plantar flexor muscles work at a high effort level relative to maximal capacity, suggesting that declines in the capacity of this muscle group with age can have a significant effect on gait biomechanics (Kulmala et al., 2016; Kulmala et al., 2020). The results of the current study suggest that runners who train at faster paces demonstrate greater propulsive GRF, so helping runners to maintain running speed as they age may be an important contributor to running performance.

Training volume (i.e., weekly running mileage) can also mitigate age-related changes in running biomechanics (Paquette et al., 2017). When younger and middle-age runners were matched for average training volume (young = 48.3 ± 23.2 km/week, middle-age = 47.5 ± 24.6 km/week), there was a 10.5% decreased peak plantarflexor moment in the middle-age runners, but no other significant differences in lower extremity joint kinetics or GRF between groups (Paquette et al., 2017). Although the average training volume of the participants in the current study was lower than the previously mentioned study, there was not a significant negative relationship between age and weekly running mileage, suggesting that training volume may have a protective role against age-related changes in running biomechanics in this cohort of female runners. However, higher training volumes have been associated with running-related injuries (McKean et al., 2006), particularly in master female runners (Loudon & Parkerson-Mitchell, 2022). The optimal training volume for female recreational runners to mitigate age-related changes in running biomechanics is currently unknown, though Loudon and Parkerson-Mitchell (2022) have suggested that master female runners limit their training volume to less than 30 miles per week to minimize risk of injury.

One limitation of this study is the heterogeneity of this group of female runners. There was a relatively wide range of running paces and weekly running volume. Additionally, foot strike pattern and running shoes were not standardized, and these factors can influence running biomechanics. However, the authors prioritized external validity of the findings by allowing participants to run in their natural style and preferred running shoes. Finally, because of the cross-sectional design of this study, no conclusions can be made about the natural effects of aging on the measured variables.

In conclusion, female recreational runners demonstrate decreased training and 5K paces with increased age. After controlling for self-selected running speed, there were no significant relationships between age and running biomechanics. Several biomechanical variables were moderately to strongly correlated with running speed, including peak plantarflexion moment and vertical and horizontal GRF. Assisting runners in maintaining training speeds with increased age may help mitigate age-related changes in running biomechanics.

CHAPTER 3

ISOMETRIC KNEE EXTENSION AND HIP ABDUCTION STRENGTH ARE NEGATIVELY CORRELATED WITH AGE IN FEMALE RECREATIONAL RUNNERS

3.1 Introduction

Running into older age helps to maintain cardiorespiratory fitness, healthy body composition, and overall physical function (Mckendry et al., 2018). Additionally, running is associated with decreased all-cause mortality and disability (Chakravarty et al., 2008; D.-C. Lee et al., 2014). However, running alone does not preserve muscle strength in aging endurance runners (Harridge, Magnusson, & Saltin, 1997; Mckendry et al., 2018). While strength- and power-trained older athletes demonstrate similar muscle strength to young, healthy controls, older endurance athletes demonstrate similar muscle strength to older non-athletes (Mckendry et al., 2018).

On average, muscle strength declines at a rate of 2 – 4% per year with increasing age (Mitchell et al., 2012). Although isometric and concentric muscle strength decline with age, eccentric muscle strength is relatively preserved with increased age (Porter, Vandervoort, & Kramer, 1997; Roig, 2010). Muscle strength and function are important for aging adults to maintain physical function and mobility, such as stair climbing, rising from a chair, and activities of daily living (Hairi et al., 2010; Jung & Yamasaki, 2016; Mitchell et al., 2012; Stenroth et al., 2015). Furthermore, decreased muscle strength is associated with all-cause mortality (Volaklis, Halle, & Meisinger, 2015). In running, muscle strength contributes to body weight support during the first half of stance (stance phase absorption) and forward movement of the center of mass during the second half of stance phase (stance phase generation). Eccentric muscle activation (i.e., muscle lengthening) of the knee extensors, plantarflexors, and hip abductors occurs during stance phase absorption to store energy and absorb shock, and concentric muscle activation (i.e., muscle shortening) of the knee extensors, plantarflexors, and hip extensors and abductors occurs during stance phase generation to propel the center of mass forward (Novacheck, 1998). A recent study suggests that the knee extensors and plantarflexors contract “quasi-isometrically” during running to efficiently store and transfer tendon elastic strain energy (Monte, Baltzopoulos, Maganaris, & Zamparo, 2020), functionally acting as tensioners to the tendons (Novacheck, 1998). Muscle preactivation prior to initial contact, particularly in the gastrocnemius, rectus femoris, and biceps femoris muscles, may be important in maintaining leg stiffness during stance (Tam et al., 2019). Lower extremity strength is positively correlated to leg stiffness (Chen et al., 2022), which has been associated with improved running economy (Barnes et al., 2014). Greater muscle strength may allow for a stiffer leg “spring,” which promotes improved efficiency with storage and release of energy during running. Older runners demonstrate differences in running biomechanics compared to younger runners, including decreased running velocity, shortened step length, decreased ankle and knee joint excursion, decreased ankle and knee joint stiffness, and decreased plantarflexion moment (Bus, 2003; Devita et al., 2016; Diss et al., 2015; Fukuchi & Duarte, 2008; Fukuchi et al., 2014; Powell & Williams, 2018). It has been suggested that decreased muscle strength in older runners may contribute to these age-related changes observed in running biomechanics (Karamanidis & Arampatzis, 2005; Karamanidis et al., 2006).

In addition to age-related declines in muscle mass and muscle strength, females experience hormonal changes during menopause that affect musculoskeletal health. Estrogen has a positive effect on muscular function via preservation of muscle mass and generation of muscle force; therefore, following the steep decline of estrogen that occurs during menopause, both skeletal muscle mass and the quality of muscle contractions are compromised (Collins et al., 2019; Enns & Tiidus, 2010; Geraci et al., 2021). Research has shown menopause is associated with decreased lean muscle mass, decreased muscle strength, and decreased muscle power (Bondarev et al., 2018; V. Messier et al., 2011; S. Sipilä et al., 2015; Sowers et al., 2007; Sternfeld et al., 2005). Physical activity has been shown to be beneficial to muscle strength in menopausal women (Bondarev et al., 2018; Sarianna Sipilä et al., 2020) and in aging adults (Ramsey et al., 2021), but the effect of age (and subsequently menopause) on lower extremity muscle strength specifically in female runners has not been well-studied. The purpose of this study was to determine if there is a relationship between age and lower extremity muscle strength in female recreational runners. The hypothesis was that there will be a negative relationship between age and isometric and concentric strength, but no relationship between age and eccentric strength. An exploratory secondary analysis was performed post hoc to determine if there is a relationship between lower extremity muscle strength and self-selected running pace.

3.2 Methods

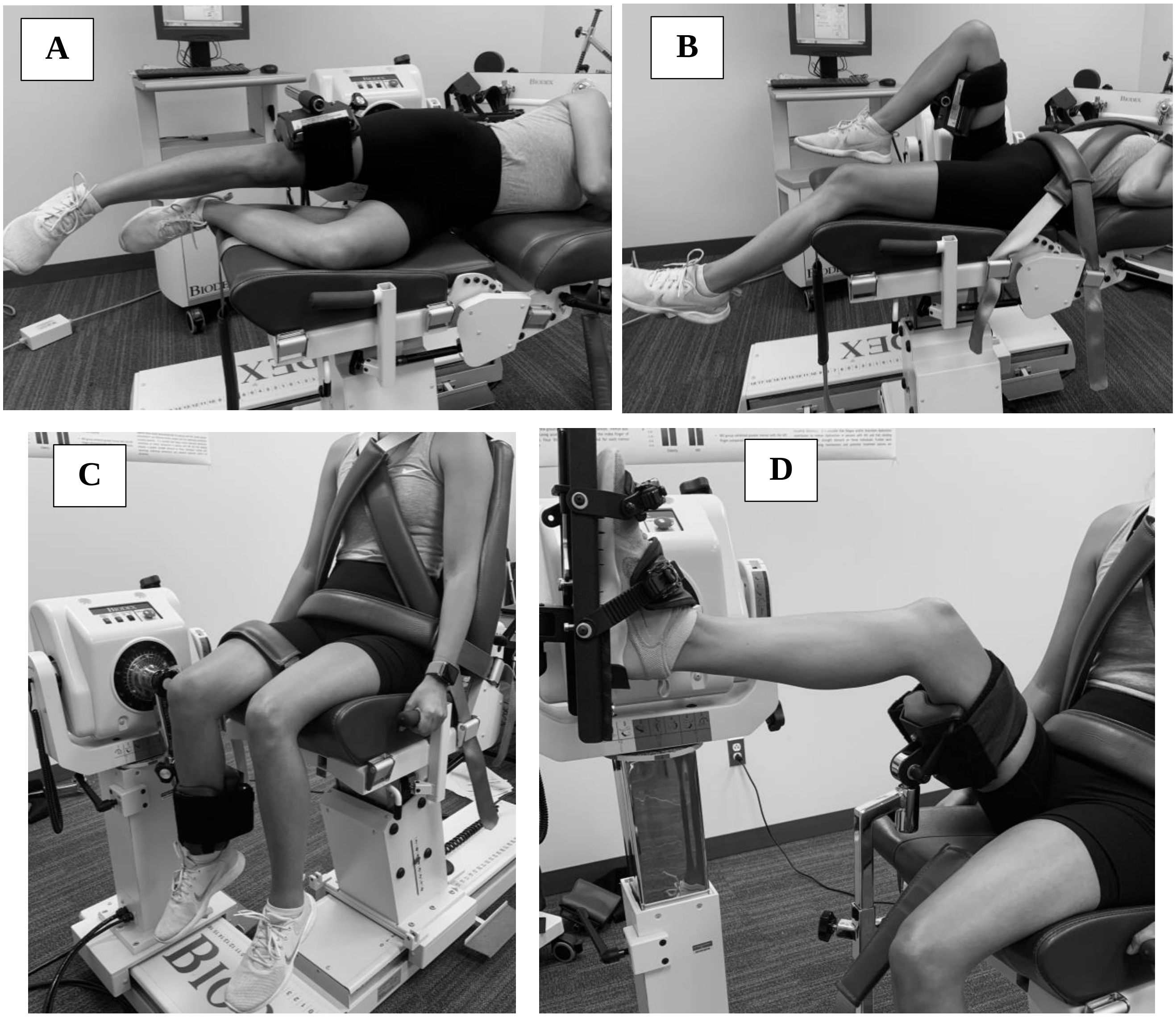
This study was approved by the Old Dominion University Institutional Review Board. Female recreational runners were recruited from the local running community through social media and word of mouth. Participants qualified for the study if they were 25 – 65 years of age and running at least 10 miles per week on average for at least the past 6 months, with the shortest run at least 3 miles. Exclusion criteria included any lower extremity injury or surgery in the past 6 months that would have a negative effect on training (Yamato et al., 2015), musculoskeletal pain affecting running mechanics, current pregnancy, or less than one year postpartum. Participants were educated on the purpose of the study and signed an informed consent document prior to participation. They were asked to avoid intense exercise 48 hours prior to data collection.

The participants completed a questionnaire that included information regarding health history, running history, and current running and training. Participation in resistance training (RT) was included in the questionnaire: “Do you regularly participate (at least once per week) in strength training (resistance exercises in which the last repetition feels difficult to complete)?”

Strength testing. As part of a larger study design, participants performed a 15-minute submaximal run on a treadmill followed by at least 5 minutes of rest prior to strength testing. The treadmill protocol included the participants running at self-selected paces for a 5-minute warm-up, 5-minutes at an “easy” training pace (JOG), and 5-minutes at a 5K race pace (RUN). The participant’s dominant lower limb was used for all muscle strength testing. The dominant limb was determined by asking the participants with which limb they would kick a soccer ball (Wilkerson et al., 2004). An isokinetic dynamometer (Biodex Multi-Joint System PRO, Biodex Medical Systems, Inc., New York) was used to measure the following variables: maximum isometric and isokinetic hip abduction (HipABD), hip extension (HipEXT), knee extension (KneeEXT), and plantarflexion (PlantarFLEX) strength (Nm). Isometric testing consisted of 3 repetitions of a 5-second maximum voluntary contraction (MVC) with 30 seconds of rest in between each trial. The highest MVC (peak isometric force) normalized to body mass (Nm/kg) was used for statistical analysis. Isokinetic testing (concentric/eccentric) was performed for 5 trials at 120°/s (Ford et al., 2013; Taylor-Haas et al., 2014). Participants were instructed to push against the pad as hard as possible during the concentric portion and to resist the pad as hard as possible during the eccentric portion (Li, Newton, Shi, Sutton, & Ding, 2019). Standardized verbal encouragement was provided to all participants during data collection to maximize performance (Taveira et al., 2021). The highest values of peak torque for the concentric and eccentric phases normalized to body mass (Nm/kg) were used for statistical analysis.

The manufacturer’s recommended testing positions were used for muscle strength testing. For hip abduction, the participant was positioned in side-lying, with the dynamometer axis of rotation superior and medial to the greater trochanter and the arm of the dynamometer strapped to the thigh just above the participant’s lateral femoral condyle of the testing limb. The participant’s hip was placed in 0° of hip abduction for the isometric tests (Figure 3A). For hip extension, the participant was positioned in supine, with the dynamometer axis of rotation superior and anterior to the greater trochanter and the resistance pad positioned just superior to the popliteal crease (Keep, Luu, Berson, & Garland, 2016; Masuda, Kikuhara, Takahashi, & Yamanaka, 2003; Zapparoli & Riberto, 2017). The participant’s hip was placed in 90° of hip flexion for isometric testing (Keep et al., 2016) (Figure 3B). For knee extension, the participant was positioned in a seated position with a seatback tilt of 85° and the dynamometer axis aligned through the lateral femoral condyle. The participant’s knee was placed in 90° of knee flexion (Bohannon, Magasi, Bubela, Wang, & Gershon, 2012) for isometric testing (Figure 3C). Plantarflexion was tested in a seated position with 85° of seatback tilt and 40° of knee flexion, with the dynamometer axis of rotation aligned with the fibular malleolus. The ankle was placed in 0° of plantarflexion for isometric testing (Webber & Porter, 2010) (Figure 3D). A single tester collected all trials of strength testing to minimize potential interrater error.

Figure 3. Positioning for Isometric Strength Testing. A. Hip abduction, B. Hip extension, C. Knee extension, D. Plantarflexion.



Statistical Analysis. Histograms and P-P plots were visually inspected to confirm data normality, and scatterplots of standardized residuals versus standardized predicted values were visually inspected to confirm data linearity. Outliers were identified as data values with a standardized residual greater than 3. Only one data value was identified as an outlier, and the analysis was performed both with and without that data point to confirm that the outlier was not an influential case. Pearson's product moment correlation coefficient was used to determine the relationship between age and isometric and isokinetic (concentric and eccentric) strength. For the secondary exploratory analysis, Pearson's product moment correlation coefficient was used to determine the relationship between strength and JOG and RUN pace. Alpha level was set at .05.

3.3 Results

Fifty-four subjects participated in this study (ages 27 – 65 years). Isokinetic hip abduction strength data is unavailable for 11 participants, as these participants were likely unable to overcome the minimum threshold for initiation of the protocol (38 Nm). Demographic information is presented in Table 5. There was a significant negative correlation between age and isometric hip abduction strength ($R = -.32$, $p = .017$) and age and isometric knee extension strength ($R = -.28$, $p = .041$). There were no significant correlations between age and any other measures of isometric or isokinetic strength (p's $> .116$). Peak isometric force data is presented in Figure 4.

JOG pace was moderately correlated with eccentric HipABD and isometric KneeEXT and weakly correlated with isometric and concentric HipABD, isometric, concentric, and eccentric HipEXT, and isometric PlantarFLEX (Table 6). RUN pace was moderately correlated with isometric KneeEXT and weakly correlated with isometric, concentric, and eccentric HipABD, isometric and concentric HipEXT, and isometric PlantarFLEX (Table 6).

Table 5. Participant Demographic Information.

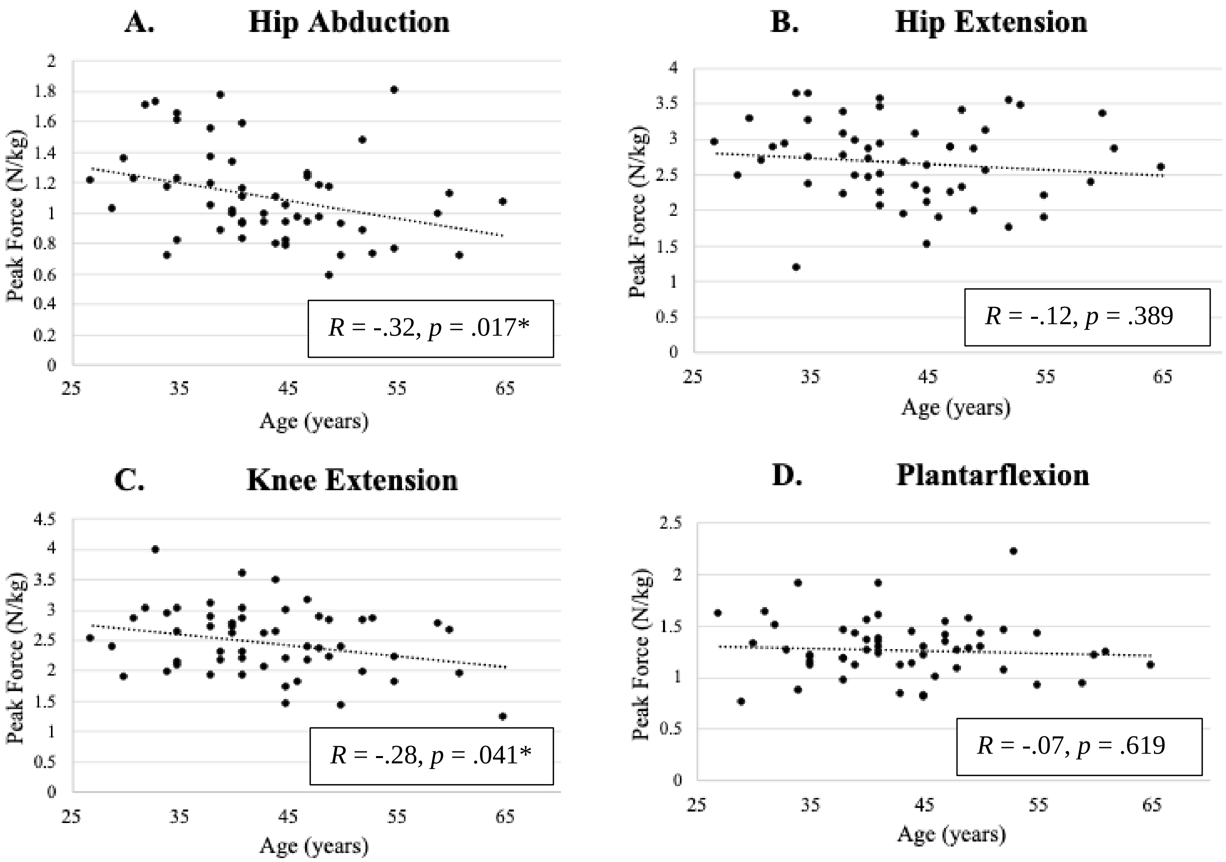
Participant Characteristics (n = 54)	**M ± SD**
Age (years)	43.2 ± 8.4
Body Mass Index (kg/m^2)	23.6 ± 2.6
Average miles run per week (mi/week)	22.9 ± 13.0
JOG pace (m/s)	2.62 ± .35
RUN pace (m/s)	3.00 ± .44

Table 6. Results of Correlation Analysis Between Strength and Running Pace.

Strength Variable (N/kg)	**M ± SD**	**JOG *R***	**JOG *p*-value**	**RUN *R***	**RUN *p*-value**
HipABD isom	1.10 ± .30	.34*	.011	.35*	.011
HipABD conc	1.10 ± .35	.39*	.011	.39*	.010
HipABD ecc	1.63 ± .36	.44*	.003	.39*	.009
HipEXT isom	2.66 ± .56	.31*	.025	.27*	.047
HipEXT conc	3.48 ± .67	.27*	.045	.27*	.046
HipEXT ecc	3.51 ± .62	.29*	.033	.26	.054
KneeEXT isom	2.45 ± .55	.40*	.003	.44*	< .001
KneeEXT conc	1.72 ± .40	.11	.435	.17	.220
KneeEXT ecc	2.80 ± .67	-.03	.814	.04	.758
PlantarFLEX isom	1.26 ± .28	.30*	.031	.29*	.033
PlantarFLEX con	1.56 ± .42	.25	.075	.24	.084
PlantarFLEX ecc	1.85 ± .46	.16	.246	.17	.226

HipABD = hip abduction, HipEXT = hip extension, KneeEXT = knee extension, PlantarFLEX = plantarflexion, isom = isometric, conc = isokinetic concentric, ecc = isokinetic eccentric.
*denotes $p < .05$.

Figure 4. Peak Isometric Force of the Lower Extremity.



3.4 Discussion

The purpose of this study was to determine if there is a relationship between age and lower extremity muscle strength in female recreational runners. In partial agreement with the hypothesis, there was a significant negative correlation between age and isometric hip abduction and knee extension strength. However, no other significant correlations between age and lower extremity muscle strength were found. Several of the strength measures were weakly to moderately correlated with training and 5K running pace.

Hip abduction strength is important in runners for pelvic and lower extremity stability and control. Female runners demonstrating increased hip adduction are more likely to develop patellofemoral pain (Noehren et al., 2013), suggesting the hip abductors are integral to more than just frontal plane control. Hip abductor muscle weakness is also associated with iliotibial band syndrome in runners (Fredericson et al., 2000; Mucha, Caldwell, Schlueter, Walters, & Hassen, 2017). In a survey of masters female runners, the most common overuse injury site was the hip and gluteal region (Loudon & Parkerson-Mitchell, 2022). Targeted hip abductor muscle strengthening may be in important for aging female runners to mitigate injury risk; however, future injury risk cannot be inferred from this study because the participants were healthy runners at the time of data collection.

Knee extension strength is important in runners for numerous reasons. The knee extensor muscle group is the primary contributor to support during the braking phase of running gait (Hamner et al., 2010); therefore, decreased knee extension strength with increased age may lead to decreased shock absorption capacities during running. Greater knee extension strength is related to increased leg stiffness during running (Chen et al., 2022), which has been associated with a more efficient running economy (Li et al., 2019). Decreased knee extension strength with increased age may contribute to the decreased running velocity observed in older runners by contributing to a decline in leg stiffness, leading to a less efficient running economy. In a longitudinal study of male (mean age = 58.6 years) and female (mean age = 57.1 years) runners, there was a significant decrease in isometric knee extension and knee flexion strength with increased age (about 5 years between strength tests, 4 – 5% decrease in strength per year), but no significant change in isokinetic concentric knee strength (Marcell, Hawkins, & Wiswell, 2014). Finally, although not specific to runners, a systematic review and meta-analysis concluded that knee extensor muscle weakness is related to an increased risk of knee osteoarthritis (Øiestad, Juhl, Eitzen, & Thorlund, 2015) and would therefore be an important variable to assess in aging runners.

Although endurance running alone does not prevent age-related changes in muscle strength (Mckendry et al., 2018), it may delay the onset of decreased muscle strength (Crane, MacNeil, & Tarnopolsky, 2013). Surprisingly, the majority of the strength variables investigated in this study were not correlated with age. In a study of mixed-sex younger (20 – 36 years) and older (55 – 71 years) runners, the older runners demonstrated decreased strength in isometric hip abduction, hip extension, and plantar flexion, but not knee extension compared to the younger runners (Fukuchi et al., 2014). Potential reasons for differences in results compared to the current study are variance in the specific testing positions (hip extension and plantarflexion were assessed in prone, compared to supine and seated, respectively, in the current study) and the use of a handheld dynamometer (Biodex system was used in the current study), in addition to a wider age range compared to the current study. In a study of male master runners (40 – 88 years), the isokinetic knee extension torque (60°/s) was similar among runners in their 40s, 50s, and 60s, but significantly declined in the runners in their 70s and 80s (Tarpenning et al., 2004). If female runners in their eighth and ninth decade were recruited for the current study, it is likely that there would be greater strength declines in these older ages. While the average rate of muscle strength decline is 2 – 4% per year in aging adults (Mitchell et al., 2012), the average decrease in strength between runners in their 30's and 60's in the current study was .8% and .9% per year for isometric knee extension and isometric hip abduction, respectively. This suggests that endurance running may mitigate decreases in muscle strength that occur with natural aging. Despite the lack of significant relationships with age, this study found several measures of muscle strength were significantly correlated to running pace. In a study of male marathon runners (age range 23

– 67 years), marathon race pace was moderately correlated to overall isometric strength (Nikolaidis, Del Coso, Rosemann, & Knechtle, 2019). Additionally, in a study of sub-elite male and female runners (ages 18 – 60+ years), lower extremity muscle strength was a significant predictor of running economy (Quinn et al., 2011). In further support of the importance of lower extremity strength on running, strength training has been found to increase running economy in distance runners (Johnston et al., 1997; Støren et al., 2008). Støren et al. (2008) suggest that the primary effects of strength training in runners are neural and recruitment pattern adaptations. Increased muscle strength may promote a more efficient running stride by allowing the muscles to function at a lower percentage of maximum capacity with each stride. Promoting muscle strength in aging female runners (i.e., resistance training) may mitigate the age-related slowing of running pace observed in older runners.

There was a high percentage of participants in the current study reporting resistance training at least 1x/week (45 participants, 83%). Because there was only a small proportion of participants who did not participate in resistance training 1x/week (9 participants, 17%), separate analyses were not performed between those who did and those who did not participate in resistance training. Regardless, our results and the current literature suggest that targeted strengthening of the knee extensor and hip abductor muscles are important for aging female runners. Because running alone does not preserve muscle strength in older adults, resistance training is recommended in this population (Marcell et al., 2014). While eventual age-related changes in muscle function are inevitable, increased muscle strength achieved through resistance training may provide a greater “reserve” to postpone the decline of muscle function (Mckendry et al., 2018).

One limitation of this study is the heterogeneous participant population. Running volume, running speeds, and running and training history (including cross-training and resistance training) were not controlled for. However, the span of running histories/training allow the results of this study to be pertinent to the general female runner. Additionally, the joint excursion range for the isokinetic strength testing was not standardized.

In conclusion, isometric knee extension and hip abduction strength are negatively correlated with increased age in healthy female recreational runners. Maintaining lower extremity muscle strength with increased age may help mitigate age-related declines in running speed.

CHAPTER 4

AGE IS NOT CORRELATED WITH KNEE JOINT STIFFNESS IN FEMALE RECREATIONAL RUNNERS

4.1 Introduction

Running is a popular and accessible form of physical activity and has been shown to decrease risk of cardiovascular and all-cause mortality (D.-C. Lee et al., 2014). The positive effects of running make it a beneficial form of activity for older adults. However, middle-age and older runners experience greater injury rates compared to younger runners (McKean et al., 2006; Nielsen et al., 2013) and demonstrate differences in running biomechanics compared to younger runners (Devita et al., 2016; Diss et al., 2015; Fukuchi et al., 2014). Older runners demonstrate decreased self-selected running pace, decreased step length, decreased ankle and knee joint excursion, decreased peak ankle moment and power, and decreased propulsive ground reaction force compared to younger runners (Bus, 2003; Devita et al., 2016; Fukuchi & Duarte, 2008; Fukuchi et al., 2014).

It has been hypothesized that biomechanical differences observed between older and younger runners are related to physiological and neuromuscular changes that occur with increased age. Physiologically, older runners demonstrate decreased maximal aerobic capacity (VO_{2max}) compared to younger runners (Trappe, Costill, Vukovich, Jones, & Melham, 1996), which is likely the primary contributor to decreased endurance performance in older athletes (Tanaka & Seals, 2008). Although aerobic economy is similar between older and younger runners, older runners work at a higher percentage of their VO_{2max} compared to younger runners (Beck et al., 2016). From a neuromuscular perspective, older runners demonstrate decreased knee extension strength and decreased tendon stiffness compared to younger runners

(Karamanidis & Arampatzis, 2005). The knee joint plays an important role in energy absorption and storage of elastic energy (Jin & Hahn, 2018), and knee joint stiffness has been associated with running economy (Tam et al., 2019).

Quasi joint stiffness is a composite variable that incorporates both kinematic (joint motion) and kinetic (joint torque) variables and represents the resistance of a joint to displacement by torsional force. Increased knee joint stiffness is associated with decreased oxygen cost during running (improved running economy) (Tam et al., 2019). Knee joint stiffness is a major contributor to leg stiffness (Arampatzis, Brüggemann, & Metzler, 1999), which has also been positively associated with improved running economy (Barnes et al., 2014). Knee joint stiffness is positively related to rectus femoris activation (Tam, Santos-Concejero, Coetzee, Noakes, & Tucker, 2017), and increased leg stiffness is correlated to greater knee extension strength (Chen et al., 2022). Decreased knee extension strength and possible subsequent decrease in knee joint stiffness in older age may contribute to the decreased running speed observed in aging runners. Few studies have investigated the relationship between age and knee joint stiffness during running. Two studies concluded that older runners demonstrated decreased knee joint stiffness compared to younger runners; however, one study only included male runners (Diss et al., 2015) and the other study did not specify the sex of the participants (Powell & Williams, 2018). Because of the biomechanical and physiological differences between male and female runners (Boyer et al., 2017; Ferber et al., 2003), it is important to consider sex-specific analyses when studying the effects of age in this population.

The purpose of this study is to determine the relationship between age and knee joint stiffness (and its components) in female recreational runners. The hypothesis is that there will be a negative relationship between age and knee joint stiffness (i.e., older participants will demonstrate decreased knee joint stiffness). A secondary purpose is to determine the relationship between knee extension strength and knee joint stiffness. The hypothesis is that knee extension strength will be positively correlated to knee joint stiffness.

4.2 Methods

This study was approved by the Old Dominion University Institutional Review Board. Female recreational runners were recruited from the local running community through social media and word-of-mouth. Inclusion criteria were as follows: ages 25 – 65 years old, running at least 10 miles (16 km) per week on average for at least the past 6 months with the shortest run of the week at least 3 miles, and comfortable running on a treadmill. Participants were excluded if they had any lower extremity injury or surgery in the past 6 months that would have any negative effect on training (Yamato et al., 2015), musculoskeletal pain affecting running mechanics, currently pregnant, or less than 1 year postpartum. Participants were educated on the purpose of the study and signed an informed consent document prior to participation. Participants were asked to avoid intense exercise 48 hours prior to data collection. Leg dominance was determined by asking participants with which limb they would kick a soccer ball (Wilkerson et al., 2004). Participants wore their own running shoes.

After measuring height (m) and body mass (kg), twenty-nine reflective markers were attached following anatomical landmarks using double-sided tape: bilateral anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), iliac crests, medial and lateral femoral epicondyles, lateral & medial malleoli, heel, and first, second, and fifth metatarsal heads, spinous process of C7, spinous process of T10, manubrium, xiphoid, bilateral acromion, and right scapula. Thigh and shank clusters (4 markers each) were also placed bilaterally. The medial ankle and medial knee markers were removed following the calibration trial; the remaining markers (including the clusters) were used for segment tracking. Kinematics were collected using a 9-camera motion capture system (Vicon Nexus 2.10, 100 Hz) and a split-belt instrumented treadmill (Motek Medical, Netherlands, 1000 Hz).

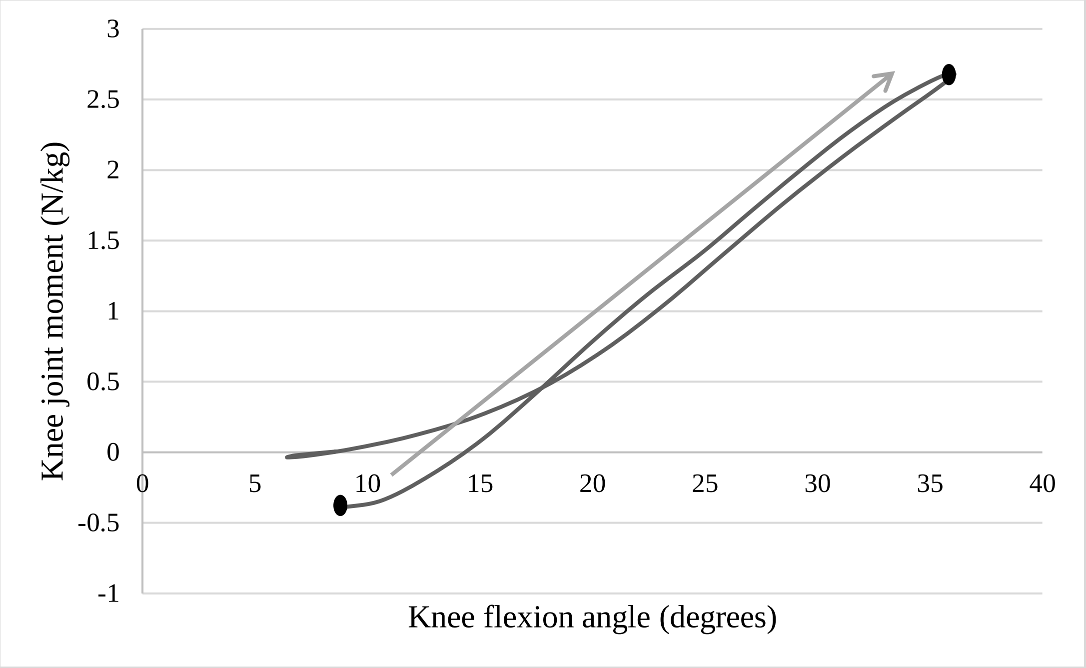
Following the static calibration trial, the participants ran for 5 minutes at their self-selected warm-up pace for treadmill familiarization. Next, the participants ran for 5 minutes at their self-selected “easy” training pace (JOG), which was described to participants as a comfortable pace that they could easily sustain while being able to hold a conversation (Agresta et al., 2018; Hannigan et al., 2018). Finally, the participants ran for 5 minutes at their self-selected 5K pace (RUN), which was described to the participants as a pace that is challenging but that could be sustained for at least 20 minutes as if running a 5K race. Data were collected for 30 seconds during the fourth and fifth minute for JOG and RUN paces.

Isometric knee extension strength was measured following the treadmill protocol using an isokinetic dynamometer (Biodex Multi-Joint System PRO, Biodex Medical Systems, Inc., New York). Participants were positioned in seated with the dynamometer axis aligned through the lateral femoral condyle and the knee placed in 90° of knee flexion. Participants performed 3 repetitions of a 5-second maximum voluntary contraction (MVC) with 30 seconds of rest in between each trial. The highest MVC normalized to body mass (Nm/kg) was used for statistical analysis. Standardized verbal encouragement was provided to all participants during data collection to maximize performance (Taveira et al., 2021).

Data processing. Visual 3D v6 (C-motion, Inc.) was used for data processing. A 6-DOF model was used for the bilateral lower extremities and trunk. The pelvis segment was defined using the bilateral ASIS and PSIS markers, using the Helen Hayes model to define the hip joint center (Davis et al., 1991). The thigh segment was defined using the hip joint center and the lateral and medial femoral epicondyle markers. The midpoint of the lateral and medial femoral epicondyle markers was used to define the knee joint center, which was used with the lateral and medial malleoli markers to define the shank segment. The ankle joint center was defined as the midpoint between the lateral and medial malleoli markers, and the foot segment was defined using the ankle joint center and the first and fifth metatarsal head markers. The C7, T10, manubrium, and xiphoid markers were used to define the thorax. Kinematic data was interpolated using a least-squares fit of a third order polynomial with a three data point fitting and a maximum gap fill of 10 frames. Kinematic and force plate data were smoothed using a fourth-order Butterworth low-pass filter of 10 Hz (Bisseling & Hof, 2006; Kristianslund et al., 2012; Radzak et al., 2017). The right-hand rule with a Cardan rotational sequence (Sagittal-Frontal-Transverse) was used for 3D angular calculations. Newtonian and Euler three-dimensional equations of motion were used for inverse dynamics calculations (Winter, 2009); internal joint moments were calculated and normalized to body mass. Initial contact was defined as the first frame the vGRF is ≥ 20 N and toe-off was defined as the first frame the vGRF is < 20 N (Karamanidis et al., 2006). Of note, one participant was excluded from the JOG analysis because her gait did not include a flight phase, and 2 participants were excluded from the RUN analysis due to data collection issues.

Knee joint stiffness was calculated as the quotient of change in sagittal plane knee joint moment (Nm/kg) and the change in knee flexion angle (degrees) during the eccentric phase of stance, which was defined as the period from initial contact to the time of peak knee extension moment (Figure 5). The change in knee joint moment and change in knee flexion angle were also extracted for analysis. Knee joint stiffness, change in knee joint moment, and change in knee flexion angle were calculated from an average of 14 strides.

Figure 5. Knee Joint Stiffness Calculation



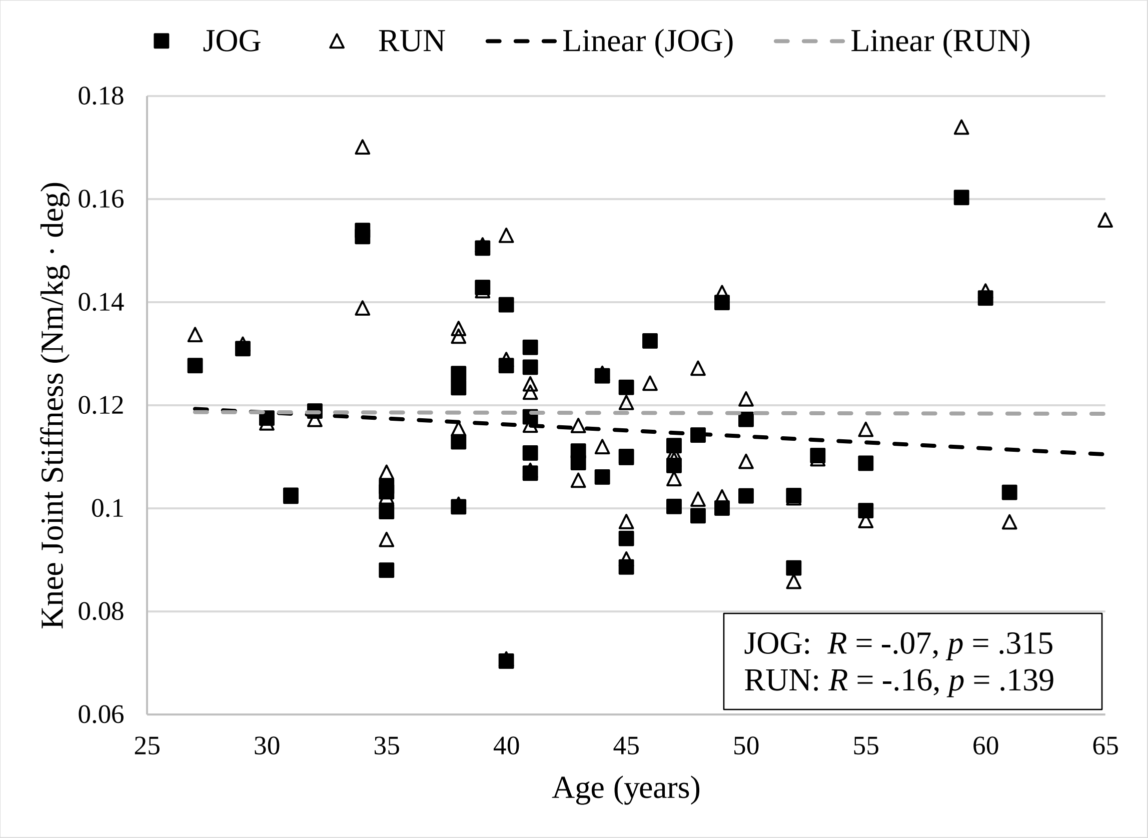
Statistical analysis. Multiple linear regression was used to determine the relationship between age and knee joint stiffness from the last minute of both JOG and RUN paces, and between age and change in knee joint moment and age and change in knee flexion angle. Running speed was included in the first regression block for all multiple linear regressions to control for self-selected pace. Pearson correlation coefficient was used to determine the relationship between knee joint stiffness and isometric knee extension strength. Statistical analysis was performed using IBM SPSS Statistics software (version 27).

Prior to performing regressions, test assumptions (i.e., normal distribution, no outliers, independent errors, and no multicollinearity) were assessed. Histograms and P-P plots were visualized to confirm normality, the Durbin-Watson statistic was used to assess independent errors (values between 1 and 3 were acceptable), and multicollinearity was evaluated by correlations between predictor variables (*r* less than .9 was acceptable) and the variance inflation factor (VIF) and tolerance statistic (VIF less than 10 and tolerance greater than .1 were acceptable) (Field, 2018). Outliers were identified as values with a standardized residual greater than 3. If an outlier was identified, the analysis was repeated without the variable to confirm that it was not an influential case.

4.3 Results

Fifty-two female runners (ages 27 – 65 years) are included in this study. One participant's change in knee joint moment and change in knee flexion angle were determined to be outliers, but exclusion of these data points did not change the overall results of the study; therefore, these values are included in the results. JOG speed was not significantly correlated to JOG knee joint stiffness ($R = -.07$, $p = .315$), and RUN speed was not significantly correlated to RUN knee joint stiffness ($R = -.16$, $p = .139$). Knee joint stiffness for JOG (mean = .12 ± .02 N/kg ▪ deg) and RUN (mean = .12 ± .02 N/kg ▪ deg) is presented in Figure 6. After controlling for speed, there were no significant relationships between age and knee joint stiffness for JOG ($R^2 = .02$, $p = .346$) or RUN ($R^2 = .03$, $p = .594$). There were also no significant relationships between age and change in knee joint moment for JOG (mean = 3.32 ± .46 N/kg, $R^2 = .03$, $p = .389$) or RUN (mean = 3.34 ± .51 N/kg, $R^2 = .13$, $p = .282$), or between age and change in knee flexion angle for JOG (mean = 29.12 ± 4.03°, $R^2 = .03$, $p = .648$) or RUN (mean = 28.74 ± 4.88°, $R^2 = .15$, $p = .868$). Finally, there was no significant correlation between isometric knee extension strength (mean = 2.41 ± .52) and knee joint stiffness for JOG ($R = .12$, $p = .403$) or RUN ($R = .09$, $p = .546$).

Figure 6. Knee Joint Stiffness for JOG and RUN.



4.4 Discussion

The purpose of this study was to determine the relationship between age and knee joint stiffness in female recreational runners. The main finding from this study is that there was no significant relationship between age and knee joint stiffness or its components for JOG or RUN after controlling for self-selected running pace. There was also no significant correlation between JOG or RUN knee joint stiffness and knee extension strength.

Considering previous literature has clearly illustrated many biomechanical variables decline with age, including knee joint stiffness in runners (Diss et al., 2015; Powell & Williams, 2018), the lack of significant findings in the current study, which is the first to focus on only female runners, is surprising. It is possible that middle-age and older runners maintain knee joint stiffness as a strategy to maintain the same energetic cost of running. As running economy does not decrease with increased age (Beck et al., 2016), and both leg and knee joint stiffness are associated with running economy (Barnes et al., 2014; Tam et al., 2019), runners may continue to “self-optimize" stiffness with increased age to manage the energetic cost of running (Moore et al., 2019). The common age-related changes in running biomechanics, such as decreased step length, decreased gait speed, and decreased lower extremity joint excursion/moments (Bus, 2003; Devita et al., 2016; Fukuchi & Duarte, 2008; Fukuchi et al., 2014), may contribute to maintaining relatively similar knee joint stiffness values across ages. In support of this notion, it has been shown that leg stiffness is relatively constant from the beginning to the end of a fatiguing run (Hunter & Smith, 2007), and runners are able to modify their leg stiffness when running on different surfaces to maintain similar biomechanics (Ferris, Louie, & Farley, 1998). Thus, it is plausible that older runners are capable of adjusting their stiffness to minimize the metabolic cost of running.

To the authors’ knowledge, few previous studies have investigated the relationship between age and knee joint stiffness. In support of our findings, Borgia, Radzak, and Freedman Silvernail (2021) report no significant differences in knee joint stiffness between younger (n = 10, 18 – 35 years) and middle-aged (n = 10, 45 – 65 years) runners (controlled pace of 4.0 m/s), but the sex of the participants is not specified. In contrast, Powell and Williams (2018) found that older runners (n = 10, 60 – 70 years) demonstrated decreased knee joint stiffness (older runners: .10 ± .01 N/kg ▪ deg, younger runners: .12 ± .02 N/kg ▪ deg, *d* = 1.40), knee joint flexion excursion (older runners: 26.3 ± 5.0°, younger runners: 33.1 ± 8.7°, *d* = .96), and peak knee extension moments (older runners: 2.13 ± .24 Nm/kg, younger runners: 2.66 ± .25 Nm/kg, *d* = 2.16) compared to younger runners (n = 9, 30 – 40 years). This study included a relatively small sample size and the sex of the participants is not specified, used a set running pace of 3.35 m/s for all subjects (current study allowed self-selected running pace), used neutral laboratory running shoes for all subjects (current study used subjects' own running shoes), and all subjects were heel strikers (current study did not control for foot strike pattern). Additionally, the older group (ages 60 – 70 years) exceeded the age range of the current study. Despite these methodological differences, the knee joint stiffness reported in the young group in Powell and Williams' (2018) study (0.12 ± 0.012 Nm/kg ▪ deg) is identical to the mean knee joint stiffness in the current study (0.12 ± .02 N/kg ▪ deg), which includes participants ages 27 – 65 years. Similarly, Diss et al. (2015) found that older male runners (n = 6, 60 – 68 years) demonstrated decreased knee joint stiffness (*d* = 1.06) compared to younger male runners (n = 8, 26 – 32 years). Diss et al. (2015) also included a middle-age group of male runners (n = 10, 50 – 54 years), and there were no significant differences in knee joint stiffness between the middle-age male runners and the younger (*d* = .48) or older runners (*d* = .95), suggesting that declines in knee joint stiffness are occurring in older ages. As Diss and co-authors normalized knee joint stiffness to leg length in addition to body weight, a direct comparison of knee joint stiffness values to the current study cannot be made. Of note, the older runners did run at a slower pace (3.34 ± .40 m/s) compared to the younger runners (4.13 ± .54 m/s), which may have contributed to the decreased knee stiffness values observed in the older runners. These runners ran at self-selected 10K race pace and finished in the top 20 participants at a regional cross country championship (Diss et al., 2015), compared to female recreational runners recruited in the current study. It is possible that if participants older than 65 years were included in the current study, a relationship between knee joint stiffness and age may be visible. However, the similar knee joint stiffness values between the young group and the current study also support the theory of runners self-optimizing knee joint stiffness throughout middle-age.

After controlling for running speed, there were no significant relationships with age and change in knee joint moment or change in knee flexion angle. There have been varied findings in the literature regarding differences in knee flexion angle and knee extension moments between younger and older runners. Devita et al. (2016) report decreased knee flexion at midstance in older runners compared to younger runners (age range = 23 – 59 years, self-selected running pace). In contrast, Harrison et al. (2018) report no differences in peak knee flexion angle at self-selected running paces among young males (22 ± 2 years), young females (25 ± 4 years), old males (50 ± 4 years), and old females (52 ± 3 years). Likewise, Fukuchi et al. (2014) did not find a significant difference in knee flexion excursion between younger (20 – 36 years) and older (55 – 71 years) runners at a controlled running pace. Powell and Williams (2018) and Harrison et al. (2018) report a significantly larger peak knee extension moment in younger compared to older runners, while multiple studies found no difference in knee joint moments between younger and middle-age or older runners (Devita et al., 2016; Diss et al., 2015; Paquette et al., 2017). When middle-age runners (mean = 58 ± 6 years) were matched for running volume and pace with younger runners (mean = 28 ± 7 years, 30 ± 7 years, respectively), there were no significant differences in knee extension moments between groups (Paquette et al., 2017). Regardless of potential differences in knee biomechanics between younger and older runners, prioritizing training that includes speed work and maintaining running pace and volume into middle- and older age may mitigate age-related changes in running biomechanics. Because there are inevitable age-related changes that occur in neuromuscular and tendinous structures, even among aging athletes (e.g., decreased muscle strength, decreased tendon stiffness) (Karamanidis &

Arampatzis, 2005), future studies are required to explore how to optimize performance in aging athletes who choose to continue participating in sport, taking into consideration these age-related changes.

Knee joint stiffness was similar between JOG pace (mean = 2.63 ± .31 m/s) and RUN pace (mean = 2.97 ± .43 m/s). The runners were required to run at least 10% faster than their JOG pace during the RUN trial, but the percentage increase was not consistent among the participants. Arampatzis et al. (1999) reported that knee joint stiffness increases with increasingly faster paces, with participants running at 2.5 m/s, 3.5 m/s, 4.5 m/s, 5.5 m/s, and 6.5 m/s. Jin and Hahn (2018) also reported increased knee joint stiffness with increased speed, with participants running at 6 different speeds between 1.8 and 3.8 m/s. The self-selected recreational running paces in the current study were likely not fast enough to elicit changes in knee joint stiffness. However, it is possible that the decreased joint stiffness observed in older runners is related to the slowed running velocity that these runners demonstrate.

The relationship between knee joint stiffness and running related injury is unclear. It is possible that there is an “optimal” level of knee joint stiffness, in which too little stiffness places increased stress on soft tissues, and too much knee joint stiffness places increased stress on bony structures, both potentially leading to overuse running injuries (Butler et al., 2003; S. P. Messier et al., 2018). Masters runners have a higher prevalence of soft tissue injuries compared to younger runners (McKean et al., 2006), which may possibly be related to the decreased knee joint stiffness observed in older runners (Powell & Williams, 2018). Because only healthy runners are included in the current study, we cannot make any conclusions about the relationship between knee joint stiffness and running related injuries.

A limitation of this study is that foot strike pattern and running shoes were not controlled. Differences in knee joint stiffness have not been found among runners wearing minimalist, traditional, or maximalist footwear (Borgia et al., 2021; Gruber, Zhang, Pan, & Li, 2021), but forefoot strikers demonstrate greater knee joint stiffness compared to rearfoot strikers (Hamill, Gruber, & Derrick, 2014). However, the authors did not want to influence the participants' natural running gait by controlling foot strike pattern.

In conclusion, there were no relationships between age and knee joint stiffness after controlling for self-selected running pace. It is possible that runners self-optimize knee joint stiffness into middle-age to manage the metabolic cost of running.

CHAPTER 5

CONCLUSION

The overall aim of this dissertation was to investigate the relationships among age, running biomechanics, and lower extremity muscle strength in healthy female recreational runners. Because of the biomechanical and physiological differences between male and female runners, it is important to consider sex-specific analyses when examining the effect of age on running biomechanics. While it is known that middle-age and older runners demonstrate differences in running biomechanics compared to younger runners, the relationship between age and running biomechanics specifically in female runners had not been well-studied prior to this line of research.

The first major finding of this dissertation is that female recreational runners demonstrate decreased self-selected running speeds (both training pace and race pace) with increased age. However, once running speed is controlled for, there are no significant relationships between age and variables of running biomechanics. As such, this study shows that running mechanics are robust in female runners into their early 60’s and lends credence that running is a safe and beneficial form of exercise for women across the age spectrum. The major finding of decreased running speed with increased age in the first aim prompted the second aim, which was to determine if age-related decreases in muscle strength contributed to decreased running speed. Female recreational runners demonstrate decreased isometric knee extension and hip abduction strength with increased age. Several other strength variables were weakly to moderately correlated with running speed, including isometric hip extension and isometric plantarflexion strength.

The findings of decreased isometric knee extension strength and decreased running speed with increased age in the second aim led to the final aim, which was to determine if knee joint stiffness was correlated with age in female recreational runners as a potential mechanism contributing to decreased running speed. Results of the final aim demonstrated no relationship between age and knee joint stiffness in female recreational runners after controlling for running speed, nor a relationship between running speed and knee joint stiffness.

Considered together, the findings of this dissertation suggest that running speed is an important factor to consider in aging female runners. While there were no variables of running biomechanics that were related to age once running speed was controlled for, there were several variables that were moderately to very strongly correlated to running speed, including vertical and horizontal ground reaction force, hip abduction moment, and plantarflexion moment, which has a foundation in the current literature. Additionally, there were several strength variables that were weakly to moderately correlated with running speed, including isometric hip abduction, hip extension, knee extension, and plantarflexion. Thus, preserving lower extremity muscle strength in these muscle groups may contribute to the ability to sustain running speed into older age. Greater force generating capacity and optimal motor recruitment patterns in lower extremity muscle groups may also allow for a more efficient use of the muscles during an endurance activity such as running.

There are practical implications of these results. First, female runners should consider strength training, particularly the muscles of hip abduction and knee extension, to help mitigate age-related declines in muscle strength and physical function. In addition to hip abduction and knee extension strengthening, plantarflexion and hip extension strengthening may also contribute to preserving running pace into middle- and older age. Strength training is related to increased rate of force development, coordination of motor unit recruitment, and increased musculotendinous stiffness, which can all promote improved running efficiency. Additionally, prioritization of speed and/or tempo workouts in female runners may help mitigate age-related slowing of running pace.

Future studies should consider female runners into an older age range. It is likely that the participants in this study represent a younger and middle-age group of female runners, and any running biomechanical changes occurring with age may be subtle into the early 60’s. It is likely that there are more dramatic physiological and biomechanical changes occurring in female runners greater than 65 years. Alternatively, female runners who continue to run successfully into older age may have adopted strategies and running biomechanics that allow them to successfully continue running; studying runners in more advanced ages may provide further insight into treatment strategies that promote longevity in running participation. Intervention studies are warranted to determine if lower extremity strengthening and speed workouts can maintain or even improve running speed in middle-age and older female runners. Finally, future studies should consider the specific effects of menopause on running biomechanics, muscle strength, and training in middle-age female runners because of the hormonal influence of estrogen on muscular structure and function. In order to provide evidence-based training and rehabilitation recommendations for aging female runners, it is important to understand the female-specific effects of aging on running biomechanics.

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Education

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Professional Appointments

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2016 – 2022	Physical Therapist, Urology of Virginia, Virginia Beach, VA
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Credentials

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Select Publications

Hamilton H, Mariano M, Kakar RS. Prevalence and Associated Factors of Urinary Incontinence in Female Recreational Runners. *Journal of Women's and Pelvic Health Physical Therapy*. 2023;47(2):75-89.

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