The Effects of Resistance Training on Running Economy and Plantarflexor Function in Middle-Age Runners

Zoey C. Kearns

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THE EFFECTS OF RESISTANCE TRAINING ON RUNNING ECONOMY AND PLANTARFLEXOR FUNCTION IN MIDDLE-AGED RUNNERS

By
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Abstract

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Endurance running exposure alone may not be sufficient to slow the age-related decline in plantarflexor function that is also thought to contribute to declines in running economy. Thus, it is important to identify interventions beyond running alone, plantarflexor-focused resistance training, that could help maintain plantarflexor function and “youthful” metabolic costs in aging runners. PURPOSE: To assess the influence of three types of resistance training interventions on running economy (RE), plantarflexor function, and Achilles tendon (AT) stiffness in middle-aged runners. METHODS: Twenty-six middle-aged runners (51±5 yrs) participated in one of three different 10-week resistance training interventions: 1) heavy resistance training, 2) heavy resistance training + plyometrics, and 3) endurance resistance training + plyometrics. Laboratory testing for RE, peak plantarflexor torque, and AT stiffness during isometric contractions occurred before and after the interventions. A mixed-design repeated measures ANOVA was used to address our research question and paired and independent t-tests were used to compare time and group effects, respectively. RESULTS: Relative (to \( \dot{V}O_2\)max) running economy (-2.4%, p=0.016), AT stiffness (26.1%, p=0.002), and peak isometric plantarflexor torque (26.4%, p=0.001) improved over time with no interaction or group effects. No significant interaction, time, or group effects were observed for \( \dot{V}O_2\)max and peak plantarflexor torque, peak positive ankle power, or positive and negative ankle work while running. CONCLUSION: Our results suggest that resistance training improves running economy for middle-aged, recreational runners, potentially by inducing increases in AT stiffness. We present a novel finding that multiple modalities of resistance training increase AT stiffness and improve running economy in middle-aged runners.
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Abbreviations

$\dot{V}O_2$\text{max}: maximal aerobic capacity

AT: Achilles tendon

MTU: muscle-tendon unit

GRF: ground reaction forces

1RM: one repetition maximum

COP: center of pressure

QF: quadriceps femoris

HRT: heavy resistance training

HRPT: heavy resistance and plyometric training

ERPT: endurance resistance and plyometric training

MVIC: maximal voluntary isometric contraction
Chapter I

Statement of problem

With declining global birthrates, the World’s population is growing increasingly older. In 2000, 6.9% of the World’s population was over the age of 40, by 2050, adults over the age of 40 years are expected to make up 19.3% of the World’s population (H. Tanaka & Seals, 2008). Even in healthy adults, aging decreases physiological ability to tolerate and respond to stress, increasing the risk of physical disability, chronic disease, loss of mobility, and decreased independence (Fragala et al., 2019). Physical activity and exercise help slow the rate of decline in function in aging populations (Fragala et al., 2019; Lazarus & Harridge, 2010, 2017) and decrease the risk of developing cardiovascular disease, cancer, neurological conditions, and respiratory infections (Booth et al., 2012; Lee et al., 2017; Niccoli & Partridge, 2012). Decreased time spent exercising as individuals age is due to other life priorities becoming more demanding, increasing work responsibilities, and more childcare responsibilities (Lepers & Stapley, 2016). These factors likely play a major role in the declining health of older adults.

Running is a mode of exercise with a low barrier to entry, whose popularity has exploded over the past couple decades. Road races from 5K to ultra-marathon distances worldwide are seeing increasing participation levels, primarily driven by skyrocketing participation of runners over the age of 35 (Zingg et al., 2013). The New York City Marathon, one of the premier road races in the World exemplifies this trend. Women over the age of 40 made up 24% of female finishers from 1980-1989 and by 2000-2009; this age group comprised 40% of all female finishers. Male finishers over the age of 40 increased from 36% to 53% of all male finishers in the same time period (Lepers & Cattagni, 2012). As rates of obesity and other morbidities
associated with lack of physical activity skyrocket, exercise including running plays a key role in helping an aging population maintain or increase their levels of activity.

As we age, the normal course results in declining cardiovascular fitness, decreased muscle mass (sarcopenia), loss of mobility, and increased risk of disability and chronic disease (Booth et al., 2012; Niccoli & Partridge, 2012). All of these declines result in decreased independence, severely impacting mental health and accelerating the rate of physical decline. Regular physical activity is the best strategy to combat all of these factors, with higher intensity modalities, such as running, being the most efficient options to improve quality of life.

Vigorous exercisers, e.g., marathon competitors, age at different rates than sedentary adults (Lazarus & Harridge, 2010). It has been suggested that factors other than the physical changes brought on by aging may contribute to decreased motivation to maintain activity levels. Decline in ultra-marathon performance before the age of 55 is more associated with an increasingly sedentary lifestyle than age (Zingg et al., 2013), contradicting the long-held belief that declines in athletic performance are an inevitable consequence of aging. Research shows declines in performance might be more closely related to social and lifestyle factors that ultimately reduce training exposures (Lepers & Stapley, 2016; H. Tanaka & Seals, 2008). A decrease in training load may predispose aging athletes to higher injury rate and less motivation to invest time and resources into maintaining a regular training regime and optimal performance (H. Tanaka & Seals, 2008). These performance declines with increasing age are seen in every level of runner. To help runners overcome the social and familial stressors negatively impacting their training, the focus should be on finding strategies to make running easier, i.e., more economical and less effortful, so running is more enjoyable.
Numerous biological explanations for declining performance with age have been proposed, but none that singularly explain the extent of the decline. Age-related sarcopenia and decreased testosterone explain some of the declines in performance, but not all of it (Schneider et al., 2019), while other investigations propose an increasing cost of running to be a primary factor. Reduced lactate threshold or exercise economy likely contribute to decreased performance, but most likely not as much as age-related declines in $\dot{V}O_2_{\text{max}}$ (Lepers & Stapley, 2016). Decreasing maximal aerobic capacity ($\dot{V}O_2_{\text{max}}$) is more strongly correlated with a decrease in activity level than age (Lepers & Stapley, 2016; H. Tanaka & Seals, 2008; K. Tanaka et al., 1990), making it a variable that can be positively impacted by maintaining running participation.

Tracking the change in world record performances has been suggested as a way to measure the true rate of age-related performance decline, as these individuals must be active enough to not be affected by changes due to a sedentary lifestyle. World record running times increase slowly from age 35 to between 50-60 years of age (depending on distance) and increase exponentially after age 60 (H. Tanaka & Seals, 2003). The top masters athletes may still be training at the same relative level as they did previously, but with some unknown normalization to maintain equivalent training volume and intensity (Lazarus & Harridge, 2010). Unfortunately, it is almost impossible to determine which is the cause and which is the effect between decreasing performance and decreasing training volume and intensity (Lepers & Stapley, 2016). Therefore, it is important to study various exercise interventions that aim to improve the determinants of performance in older athletes. Specifically, it would be valuable to assess the effectiveness of interventions to help master athletes maintain their performance for as long as possible.
Literature Review

Resistance training is a viable modality to slow the age-related declines in physical performance and is one of most readily accessible to a large population including runners of all ages. The aim of this review is to summarize current literature on the potential effectiveness of resistance training on running economy, Achilles tendon (AT) stiffness, and biomechanical variables related to economy in aging runners. The review also aims to determine if changes in running biomechanics and AT stiffness are related to improvements in running economy in aging runners.

Aging

Physical activity, and aerobic exercise in particular, is crucial to preserving quality of life in an aging population. Physical inactivity accelerates the rate of cognitive decline and loss of functional ability to perform daily activities, decreasing lifespan and increasing disability rate (Booth et al., 2012). Since a sedentary lifestyle is primary risk factor for debilitating conditions affecting all aspects of physical and mental health, exercise is a cost-effective way to mitigate the health care economic burden imposed by aging.

Cardiovascular System

Age is a primary risk factor for developing life-threatening conditions such as cancer, cardiovascular disease, and neurodegenerative pathologies (Niccoli & Partridge, 2012). Advancing age is a disease risk factor because humans accumulate DNA mutations with negative effects as they age, as well as traits that were favorable earlier in life, that negatively impact human health later in life. It is challenging however, to determine what are the true inevitable, biological effects of aging, instead of symptoms caused by an increasingly sedentary life most
people adopt as they age. It has been found that $\dot{V}O_2\text{max}$ is a better indicator of an individual’s level of immune, hormonal and physiological function than their chronological age (Lazarus & Harridge, 2010). Additionally, low levels of cardiovascular fitness have been established as the best predictor of mortality when compared to any clinical variable or other established risk factor (Booth et al., 2012). Maintaining cardiovascular fitness, and thus the body’s ability to circulate blood and oxygen, is an effective strategy for decreasing mortality risk.

The ability of an individual’s body to deliver oxygen and nutrients to tissue is seen as a greater limitation of performance in older adults than their ability to extract oxygen and nutrients (Carrick-Ranson et al., 2013; Lepers & Stapley, 2016). Maximal stroke volume and blood volume are mostly preserved with aging (absent any other co-morbidities), leaving maximal heart rate as the cardiovascular variable most affected by the biological forces of aging (H. Tanaka et al., 2001). The difference in oxygen delivered and extracted seems to be preserved by consistent aerobic exercise, which increases the density of mitochondria and enhances blood flow to tissues under stress (Carrick-Ranson et al., 2013). Changes in cardiovascular health may also be related changes in musculoskeletal health. Generally, muscle mass decreases with age, resulting in lower mechanical stress placed on the cardiovascular system since there is a lower requirement for muscle oxygenation. This lower cardiovascular chronic stress results in lower cardiovascular fitness, leading to more acute cardiovascular work to provide adequate oxygen and necessary nutrients to muscle tissue.

Musculoskeletal System

A large factor contributing to good physical and mental health with aging is maintaining community ambulation. In terms of preserving community ambulation with increasing age, the ability to generate power decreases, regardless of level of physical activity, but can be mitigated
by minimizing muscle loss. Sarcopenia, age-related muscle loss, is far more common in adults living in assisted living or skilled nursing facilities and predisposes these older adults to physical disability and mortality (Cruz-Jentoft et al., 2014). Walking, low-impact calisthenics, and resistance training are popular choices for increasing physical activity in older adults, though resistance training is generally considered the most high-risk of the three. Commonly cited barriers to participation of older adults in resistance training are safety, fear of increasing the risk of heart attack, stroke, or death, pain, fatigue, and a lack of social support (Burton et al., 2017). Especially considering the reluctance with which aging adults approach resistance training, it is important to focus the training on the area of the body most affected by the aging process.

The ankle plantarflexor muscle group is most affected by age during the walking. They show the greatest decrease in torque output, and angular work and power generation of all the lower extremity joints with advancing age (DeVita & Hortobágyi, 2000; Karamanidis & Arampatzis, 2005; Unhjem et al., 2019). The plantarflexors are composed of the gastrocnemius and soleus muscles (together called the triceps surae muscles) and the Achilles tendon (AT). Static imaging of the triceps surae using diagnostic ultrasound has been well established in the literature to quantify specific aspects of their architecture. Diagnostic ultrasound relies on a transducer head containing piezoelectric crystals, which produce ultrasound waves. These high-frequency sound waves reflect off of internal structures to produce grayscale images. For the best reliability of measurements, participants are typically restrained in a dynamometer with joints held at pre-determined angles. Ultrasound imaging allows for determination of muscle cross-sectional and anatomical area, pennation angle, and fascicle length (J. R. Fletcher & MacIntosh, 2018; Karamanidis & Arampatzis, 2005; Peltonen et al., 2012; Stenroth et al., 2012, 2015, 2017, 2019). Muscle fascicle length affects the speed of shortening where shorter fascicles can shorten
more quickly and produce more force by volume since more actin-myosin cross-bridges are formed (Lieber & Ward, 2011). If the muscles have a high pennation angle, the force produced by the muscles is transmitted to the AT less efficiently (Zajac, 1989). Since the elastic properties of the AT contribute to lower energetic costs, more efficient force transfer from the plantarflexors to the AT is valuable. Also, thicker muscles result in a longer moment arm (Nagano & Komura, 2003), which can be beneficial or detrimental to performance, depending on the type of activity. A longer moment arm is usually preferable for low-velocity, high-force movements, while a shorter moment arm is usually better for high-velocity, low-force movements (Nagano & Komura, 2003). Generally, the greater the muscle volume, the more force a muscle is able to generate during contractions. Ultrasound images of plantarflexor muscles are commonly collected during maximal voluntary isometric contractions. The muscle force generated against a hand-held dynamometer during these contractions appears to be positively associated with levels of positive ankle joint work, though this relationship was not evident at the knee or hip (Fukuchi et al., 2014). In addition to providing valuable imaging of muscles characteristics and architecture, diagnostic ultrasound is also a cost-effective method for imaging tendons. This is important since although these muscle characteristics can be improved with training, the rate of decline in performance is unavoidable without also addressing lower tendon stiffness.

Aging is associated with reductions in AT and quadriceps tendon stiffness (Karamanidis & Arampatzis, 2005; Stenroth et al., 2012) which is concomitant with slower muscle contraction velocity and increased time to reach peak leg press power while seated in a custom-made apparatus (Pearson et al., 2002). When considering potential age-related changes of the ankle plantarflexors, it has been postulated that performance changes are more likely due to
architectural changes of the AT rather than the muscles. AT stiffness is believed to decrease with age (DeVita & Hortobágyi, 2000; Stenroth et al., 2012), and more force generation from the attached muscle is required with a less stiff tendon to shorten the muscle-tendon unit (MTU). Longer tendons also decrease the stiffness of the MTU since they require additional myofilament overlap. The AT is fatigue resistant tendon that does not generally show a change in its mechanical properties even after running a marathon, despite measurably increased level of fatigue in the plantarflexor muscles (Peltonen et al., 2012). However, a 22% decrease in tendon stiffness in older runners (56±4.7 years of age) has been observed following a half marathon on a track, while no changes in stiffness were observed in younger runners (Ackermans et al., 2016). Static measurements of the tendon can be obtained using the same procedure and dynamometer set-up as the muscle tissue. When AT length is measured while walking using diagnostic ultrasound images in combination with motion capture or electro-goniometers, tendon force can be estimated (Arampatzis et al., 2005; Franz et al., 2015; Franz & Thelen, 2015; Karamanidis & Arampatzis, 2005; Stenroth et al., 2017, 2019; Zelik & Franz, 2017). From such tendon force estimations, tendon properties and mechanics can be calculated.

Young’s modulus provides a way to evaluate a tendon’s resistance to deformation and is calculated as the slope of the stress-strain relationship, which represents a tendon’s ability to withstand changes in length while under tension. AT stress can be calculated by dividing tendon force by free tendon cross-sectional area and represents the internal forces that neighboring structures exert on one another. Some investigations have found that older adults experience lower peak stance phase AT stress than younger participants, regardless of speed, though it must also be noted that older adults tend to have higher AT CSA (Ebrahimi et al., 2020). AT strain measures the relative deformation of the tendon, calculated by normalizing tendon elongation to
tendon length at rest (Stenroth et al., 2012). Fifty-two adults between the ages of 70-81 years had AT and triceps surae muscle architecture imaged with ultrasound while seated in a dynamometer to obtain AT stiffness, muscle thickness, fascicle length, and pennation angle. After undergoing testing of ambulatory mobility (6-minute walk test and timed up-and-go test), voluntary isometric plantarflexion strength, leg extension strength and power, and lower body lean mass were also measured. Plantarflexor strength explained most of individual variance in mobility, more than lower extremity lean mass, leg extension strength, or leg extension power. Plantarflexor strength was strongly associated with mobility, while increased mobility was associated with higher pennation angle in the soleus muscle, increased AT stiffness, and decreased muscle fascicle length. The increased pennation angle is a sign of increased cross-sectional area, which indicates more muscle mass for developing force due to decreased muscle mass to activate (Stenroth et al., 2015). The AT is responsible for most of the changes in overall length of the triceps surae MTU during stance phase of walking, meaning that shorter muscle fascicles may be more efficient at developing force since they activate a smaller muscle mass. Interestingly, sagittal plane knee joint angle does not seem to affect tendon displacement, which is surprising since it does affect plantarflexor force generation (Stenroth et al., 2019). This seems to indicate that relative tension placed on different muscle heads of the triceps surae muscle complex does not seem to affect the displacement of different areas of the AT.

A disadvantage to collecting ultrasound images during walking is current technology only allows for data collection in the sagittal plane, but we know deformations occur in the sagittal and frontal planes. It has been suggested that the coronal plane deformations may be greater than the sagittal plane deformations (Stenroth et al., 2019). We know the relative roles of the soleus and gastrocnemius become more distinctive as walking speed increases and is
matched by increasing differences between superficial and deep AT deformations as speed increases (Franz et al., 2015). Unfortunately, current technology does not support clear differentiation between layers of the AT while running, although some investigators have been able to attach an ultrasound probe that allows for measurement of AT length and forces during a running gait (Werkhausen et al., 2019). Unfortunately, these measurements only allow for simplified calculations describing AT function and the investigation did not examine muscle activation changes that could affect the results of the calculations (Werkhausen et al., 2018). The investigators did not include clear written descriptions or images of their method for keeping the ultrasound probe still enough during running to produce clear images, so replicating their methodology would be challenging. The best way to reproduce gait-induced AT and triceps surae changes for static ultrasound imaging involves taking images at multiple ankle and knee joint angles and AT lengths to mimic running and walking positions.

Biomechanical Changes

The greatest predictor of decreased quality of life is a sedentary lifestyle. For older adults, the ability to negotiate their environments safely and efficiently is key to maintaining community ambulation. It is common for activity levels to decrease with age but maintaining some level of regular physical exertion is crucial for maintaining community ambulation, decreasing fall risk, and decreasing depression risk (Beijersbergen et al., 2013; Booth et al., 2012; da Rosa Orssatto et al., 2019; Fragala et al., 2019; Unhjem et al., 2019). Even when community ambulation is maintained, gait speeds typically decrease with aging (Beijersbergen et al., 2017). The exact reason for the decrease in speed is complicated, likely involving an underuse of available muscular capacity (Franz, 2016), but the changes that accompany the decreased speed are well documented.
It has been well established that preferred walking speed declines with age (Abellan Van Kan et al., 2009, 2012; Bassey et al., 1982; Bendall et al., 1989; Himann et al., 1988; Stenroth et al., 2017). To compare walking biomechanics between a younger (20-31 years) and older group (67-81 years), the older group completed a second walking trial at the average speed preferred by the younger group (Stenroth et al., 2017). When both groups were walking at the same speed, there was no difference in triceps surae muscle function. But when the older group was moving at their (slower) preferred speed, their muscle fascicles operated in a narrower range and at lower shortening velocity. Overall, these fascicle length changes accounted for less of the overall MTU length changes than in the younger group. This finding suggests that well-documented decreases in ankle plantarflexor function may be a result of decreased preferred walking speed instead of age-related tissue changes (Stenroth et al., 2017). Since higher forces are developed at lower fascicle shortening velocities, this indicates that the older group was able to generate force more efficiently, in terms of energy cost, than the younger groups during over-ground walking.

When walking at the same speed as younger participants along an over-ground runway, older participants showed increased hip ROM and decreased ankle ROM and plantarflexion compared to the younger group. Older participants walked with more trunk forward lean, allowing them to activate their hip extensors longer into stance phase than the younger participants. Although the difference in time spent in swing and stance phase was not particularly large between groups, it was consistent enough to be significant. While in stance phase, the older group produced equal overall torque but with more contribution from the hip extensors and less contribution from the knee extensors and ankle plantarflexors. While maintaining their overall torque levels, the older groups showed different relative work contributions from the hip, knee, and ankle. In the younger group, the ankle plantarflexors provided 73% of all lower extremity
joint work, but in the older group, ankle plantarflexors provided only 51% of the overall joint work (DeVita & Hortobágyi, 2000). This indicates a distal to proximal shift of joint work during walking with aging.

Loading response and force absorption characteristics during running also change with age. It has been found that older adults run with higher initial (impact) peak vertical ground reaction force (vGRF) but a lower max peak vGRF (Kline & Williams, 2015). Since increased vertical impact force is associated with increased bone loading and tibial stress fracture risk, increased stride frequency and decreased stride length in older groups could be an attempt to mitigate the increased bone loading (DeVita & Hortobágyi, 2000; Karamanidis & Arampatzis, 2005). A high loading rate, or velocity at which force is applied to the tendon or the velocity at which the muscle shortens and applies force to the tendon, has been postulated to correlate with increased injury rate during running (Peltonen et al., 2012, 2013). Loading rates can be sensed and fine-tuned by participants to a certain extent, by asking them to run softer or heavier, so it may be an easier variable to modify in participants.

Ultimately though, when trying to help older runners, we are trying to improve their running economy, so as to make running easier. Tendon measurements allow us to calculate the AT hysteresis, or the energy lost (inefficiency) between the loading (stance) phase and unloading phase of running. Higher levels of hysteresis indicate less ankle recoil is available to aid in propulsion at toe-off (J. R. Fletcher & MacIntosh, 2018). All of these biomechanical gait changes indicate there is decreased ankle propulsive function in older adults at walking and running speeds. This suggests interventions to improve ankle propulsive function would be helpful for maintaining community ambulation with increasing age.
Exercise Interventions

With regards to exercise interventions for older adults, scientists usually study two general participant categories: sedentary adults and active or trained adults. Literature examining differences between physically active and sedentary older adults shows some biomechanical differences across a range of movements. Well-trained older weightlifters can achieve a heavier one repetition maximum (1RM) than untrained younger adults and develop leg press extension power force more rapidly than their younger counterparts (Pearson et al., 2002). Although all older adults had deficits in power development, well-trained older weightlifters were able to develop more power while stair climbing than recreationally active and sedentary older adults, but a younger untrained group generated the most power while stair climbing (Unhjem et al., 2019). The younger group and older well-trained and recreationally active adults all maintained the same preferred speed, sometimes seen as a good indicator for ability to maintain propulsive function and performance. When these groups were tested while balancing on one leg, all three older groups showed the same mean center of pressure (COP) velocity, while the younger group had a lower mean COP velocity. However, none of the sedentary group were able to successfully complete a balance trial, and only five out of 11 participants in both the well-trained and recreationally active groups successfully completed the balance test, while all of the younger participants were able to balance on one leg (Unhjem et al., 2019). This indicates that physical activity can help maintain balance ability with aging, but some level of decline is inevitable.

A 2013 review found only four investigations that involved adults over the age of 65, performed a resistance or power intervention, and included at least one biomechanical outcome measure. Analysis of these investigations concluded that changes in walking gait speed could be used as a measure of changes in muscular strength and power, despite evidence suggesting that at
most, 23% of the variation in increased walking speed is from improvements in lower extremity strength (Beijersbergen et al., 2013). This supports the important role of plantarflexor musculature in propulsion previous running investigations (Hamner et al., 2010), and improving ankle propulsion may be an effective strategy for improving gait economy.

A 2019 review of investigations involving participants at least 60 years old and including clear descriptions of the concentric and eccentric velocities of movements, comparing at least two resistance interventions performed at different speeds, and under loads of at least 60% of 1RM, found 15 investigations. Their analysis found too much variation in the methodology of the interventions and outcome measures chosen by each investigation to draw any definitive conclusions. They did note, however, that heterogeneity in the outcome measure results did not indicate any benefit in prioritizing the velocity at which the intervention movements were performed in terms of improving functional performance, rather than athletic performance (da Rosa Orssatto et al., 2019). For adults looking to maintain community ambulation, the speed of resistance training is not important, but for older athletes looking to help their running, it may be important to prioritize the speed at which they perform resistance training movements.

Since medical and fitness professionals are frequently reluctant to prescribe heavy resistance loads to older adults, Van Roie, et al. divided participants into three intervention groups with roughly equal volume (1RM percent resistance multiplied by repetitions) (2013). Participants performed the same leg press and knee extension exercises described in the previous study three times per week for twelve weeks and were expected to reach failure every set. The first, or heavy group was prescribed the guidelines recommended by the American College of Sports Medicine, two sets of 10-15 repetitions performed with resistance at 80% of 1RM. The second, or low group completed one set of 80-100 repetitions under an external load around 20%
of 1RM. The final, or low plus group completed 60 repetitions at 20% of 1RM, immediately followed by 10-20 additional repetitions at 40% of 1RM. All three groups showed similar improvements in muscle volume, but the heavy group also increased the distance they walked in a 6-minute trial and showed the largest improvements in 1RM. It must be noted that the heavy group was also able to complete their protocol in the shortest amount of time, making it more feasible for implementation outside of research. The authors noted that sustained muscle contractions at low resistance, as seen in the low group, seem to result in more central nervous system fatigue, while muscle contractions at higher resistance, as seen in the heavy group, appear to induce more peripheral nervous system fatigue, or fatigue within the muscle itself (Van Roie et al., 2013). To induce changes in muscle architecture, such as pennation angle and fascicle length, peripheral nervous system fatigue is more important.

Since leg extension and leg press do not directly stress the triceps surae, it is unsurprising that no significant, biomechanical changes were seen in walking performance in the previous two studies. When plantarflexor training was implemented in addition to the leg extension and leg press, changes in plantarflexor activation velocity and timing were seen after the 10-week intervention (Beijersbergen et al., 2017). This protocol also included 10 weeks of de-training, which allowed for resistance training induced changes at fast walking velocity to be correlated with changes in plantarflexor timing and activation. These participants were on average 72 years of age and performed three sets of 6-10 repetitions at 40-60% of 1RM. Interestingly, no correlation was found between resistance training induced changes in gait velocity and the timing or activation of the knee flexors and extensors (Beijersbergen et al., 2017). This indicates that structural changes in muscle may have a greater impact on ankle propulsive function than changes in the timing of muscle activation.
One intervention focused on implementing plyometric training in older adults (65-76 years old) using a machine similar to a leg press, except the solid platform is replaced by what is essentially a small trampoline (Franchi et al., 2019). This machine allows for introducing plyometric training with lower risk and more stability, while still challenging all lower extremity muscle groups, including the ankle plantarflexors. Participants were seated in the machine and instructed to squat to a knee flexion angle of 80-90°, and then jump off of the platform, before returning to the same squat depth. Participants completed 3 sessions per week for 6 weeks, completing three to four sets of 30 repetitions per set. After the intervention, participants showed a 27% increase in muscle power, while a younger group (20-32 years old) had a 20% increase in muscle power after participating in the same protocol. This 27% improvement matches the daily gain in power seen in a different investigation focusing on heavy resistance training for 64-year-old men. The older group also had an increase in volume and a 5.8% increase in vastus lateralis muscle thickness, while the younger group only had a 3.8% increase in muscle thickness. These results suggest plyometric training might be an effective and efficient method for counteracting sarcopenia in older adults. However, since pennation angle increased by 7.5% and fascicle length increased 8% as a result of the intervention, it may not be ideal for maximizing running performance (Franchi et al., 2019). Unfortunately, this investigation did not assess tendon stiffness as an outcome measure for the intervention, making it difficult to make associations between an important metric in plantarflexor performance and potential gait efficiency changes.

Active older adults may take part in running since it has few barriers to entry and is accessible to all and inexpensive. The population of runners that started during the jogging boom of the 1970s and 1980s is growing older, but they have not stopped running. Beyond their continued participation, some of these older runners have continued to train and perform at
relatively high levels (Lepers et al., 2021). Running, regardless of speed, helps maintain muscle strength and walking gait speed, crucial for keeping risks of mortality and morbidity low. It also engages older adults in a physically active community of loosely organized groups for every speed and distance in an accessible and inexpensive form of exercise. However, the majority of older adults experience declines in running performance due to aforementioned age-related physical changes.

**Running**

Worldwide, running has a high rate of participation among recreational athletes in all age groups. Running is a mode of exercise with a low barrier to entry (i.e., low cost and accessibility), whose popularity, especially in adults over 35 years (Zingg et al., 2013), has exploded over the past couple decades. The health benefits associated with running are well understood but running participation also leads to positive psychological changes including stress management (Gondola & Tuckman, 1982; Greist et al., 1978; Solomon & Bumpus, 1978). In a large-scale meta-analysis comparing runners and non-runners, runners tended to have higher \( \dot{V}O_2 \text{max} \) levels, and the longer a subject has been training, the greater the positive effect on \( \dot{V}O_2 \text{max} \). The other significant finding was runners tended to have a lower resting heart rate than non-runners, again showing a greater positive effect the longer a runner had been training (Hespanhol Junior et al., 2015). These findings came despite finding no significant difference in BMI or lean body mass between runners and non-runners. When it comes to overall measures of health, runners are less likely to smoke, have a lower incidence of chronic diseases, and have higher levels of cardiovascular fitness. Runners had 30% lower risk of any cause of mortality, and 45% lower risk of cardiovascular causes of death, even if they spent less than an hour a week running or ran at slow speeds (Lee et al., 2014). All of these metrics indicate that running is an
effective choice for maintaining a healthy lifestyle and minimizing imminent disease and mortality risk

**Cardiovascular System**

Running is believed to have a beneficial effect on aerobic fitness, cardiovascular function, and metabolic function (Oja et al., 2015). Running participation of at least one hour per week is associated with lower mortality risk from causes including cardiovascular disease, cancer, neurological, and infection in both men and women (Pedisic et al., 2019). When separated by gender, running was associated with a 27% lower all-cause mortality risk in men and a 34% lower mortality risk in women when compared to non-runners. When examining only the risk of mortality from cardiovascular causes, running was associated with a 30% lower mortality risk. These lower mortality risks were consistent, even with a low running frequency of one time per week or running volume of less than 50 minutes per week (Pedisic et al., 2019). These findings indicate that even minimal running is helpful in improving cardiovascular disease, and mortality, risk.

The primary mechanisms for the health benefits of running engagement may be the improvement in body composition, or the increased percentage of lean mass, and resulting reductions in resting heart rate and blood pressure (Lee et al., 2017). Improvements in resting heart rate and blood pressure from running likely result from increases in ventricular muscle wall thickness and preservation of cardiac muscle contractile properties, both allowing for more efficient circulation of blood and oxygen throughout the body (Nystoriak & Bhatnagar, 2018). Running improves blood flow to active tissues which in turn is believed to improve soft tissue mobility and extensibility (Hamann et al., 2014). Increasing blood flow improves lactate clearance as well as increasing nutrient availability, speeding tissue recovery and health.
Inflammation is a major source of pain and discomfort, particularly after physical activity, and chronic inflammation results in increased degenerative tissue changes. Running may decrease inflammatory cytokines, signaling molecules secreted by the immune system which promote inflammation, as well decreasing degenerative changes in soft tissue by reducing levels of degenerative enzymes (Sun et al., 2011). Circulation is also improved by increased capillary density, promoting greater efficiency for distributing nutrients and oxygen to working muscles. The muscles and tendons nourished by nutrients circulated by the cardiovascular system also undergo structural and functional changes as a result of running.

Musculoskeletal System

The external loading (e.g., GRF and resulting joint torques) that results from the foot colliding with the ground contribute to the mechanical loads applied to the musculoskeletal system while running. These mechanical loads without a doubt contribute to musculoskeletal injuries. Running is in fact associated with high rates and incidences of musculoskeletal injuries (Damsted et al., 2019; Nielsen et al., 2012). However, since musculoskeletal tissues can also undergo positive adaptations from these mechanical loads (Kjær et al., 2009; Mackey et al., 2008) running can have positive effects on remodeling of the musculoskeletal system and contribute to improvements in musculoskeletal health. In fact, due to the positive impact of running on BMI and improved cartilage function as a result of better joint remodeling from the impact load of running, running may actually decrease the risks of developing hip or knee osteoarthritis (Gessel & Harrast, 2019). Despite this, 40% of respondents in a Canadian survey believed distance running was a risk factor for developing knee osteoarthritis, while 78% of the surveyed health practitioners disagreed, believing running was not detrimental to joint health (Escurier et al., 2018). Although running injuries are common, there are a wide variety of
training factors that contribute to the development of running related injuries (Damsted et al., 2018, 2019; Nielsen et al., 2012). Ultimately, for most participants, the risk of injury is outweighed by the physical and mental benefits they enjoy from running.

Overall, running can improve cardiovascular disease, diabetic health, bone density, BMI, pain perception, balance, mental health, and joint cartilage function (Gessel & Harrast, 2019). Since all of these health metrics are risk factors for higher mortality rates, running participation and exposure can contribute to lower mortality risk at any age.

**Running and Aging**

Rising levels of participation in road races by adults over the age of 40 indicate the need for effective strategies to help this age demographic to maintain their ability to run. In order to slow the effects of aging that influence performance, we must first understand how running metabolic costs and its biomechanical contributors are affected by the aging process and how the aging process may be influence by continued running exposure.

*Metabolic Cost*

Despite the beneficial effects of running on the health of aging adults, performance declines are inevitable. Estimations of performance decline in marathon running are 8-10% per decade, but this is a cross-sectional study, with the rate of decline being estimated from performances by different individuals (Santos-Lozano et al., 2015). The single largest contributor to declining performance is most likely the age-related decline in maximal oxygen consumption ($\dot{V}O_2$ max), resulting in older runners having to run at a higher percentage of their $\dot{V}O_2$ max to maintain their previous pace (Lepers & Stapley, 2016). However, a lower $\dot{V}O_2$ max is more correlated with a decrease in activity level than age (Lepers & Stapley, 2016; H. Tanaka & Seals,
In fact, older runners (mean of 54.3 years during fifth marathon) completing sub 3-hour marathons during five consecutive decades have been able to limit their performance decline to 0.7% per year for 30 years following their fastest performance (Lepers et al., 2021). This demonstrates individuals can maintain the estimated rate of performance decline that had been previously calculated.

In fact, runners between 18-39 years old, 40-59 years old, and over the age of 60 years typically run with similar \( \dot{V}O_2 \) at submaximal speeds but lower \( \dot{V}O_2 \) max with increasing age suggest a higher percent of \( \dot{V}O_2 \) max in older adults (Korhonen et al., 2009). Beck et al. (Beck et al., 2016) reported similar findings in older runners (68.9±4.7 years) compared to younger runners (21.3±2.7 years). Regardless of speed, running is just more energetically expensive, in terms of the joules of energy it costs for them to move each kilogram of mass, for older runners compared to younger runners (Pantoja et al., 2016). Clearly, running is more metabolically expensive for older runners. Thus, strategies to reduce metabolic demands, i.e. improving running economy, could be useful for improving running enjoyment and retention rates for older runners.

*Musculoskeletal System*

As previously discussed, the musculoskeletal system is placed under various mechanical loads while running. Endurance runners aged 40-88 years old participating in the 17th year of a longitudinal study showed no change in muscle fiber types as they aged. At the same time, runners in their seventies and eighties had significantly less lean lower body mass and a reduced aerobic capacity compared to runners in their forties or fifties (Tarpennyng et al., 2004). Older sprinters, however, did show smaller Type II (fast-twitch) fiber cross-sectional area and smaller Type II to Type I (slow-twitch) cross-sectional area ratio (i.e., less area for Type II relative to
Type I). It is important to note that these findings are discussing fiber cross-sectional area, not absolute number of each fiber type (Korhonen et al., 2009). These sprinters also showed smaller pennation angle of the vastus lateralis with but no differences in fascicle length in older compared to younger athletes. Older runners also show less lower extremity power during vertical jumping than younger runners, which showed a strong negative association with energy cost (Pantoja et al., 2016).

Further, it has been suggested that running maintains lower, youthful levels of co-activation of the antagonist leg muscles during walking, which typically increases with age (Mian et al., 2006; Ortega & Farley, 2015), thus helping maintain youthful walking and running economy (Beck et al., 2016). Co-activation is the activation of both agonist and antagonist muscle groups during movement, decreasing the net torque at a joint, but also improving a joint’s ability to tolerate perturbations (Latash, 2018). Runners had a lower gear ratio of the triceps surae and quadriceps tendons (ratio of the moment arm of the ground reaction forces acting about the joint to the agonist tendon moment arm) than non-runners during the first half of stance phase, which allows for increased mechanical advantage (i.e., lower force/effort requirements) (Karamanidis & Arampatzis, 2005). Mechanical advantage is improved from a lower moment arm of the GRF about the knee joint, which during the eccentric quadriceps action of early stance phase reduces muscle forces to maintain joint position. This may be an age-related biomechanical adjustment while running as a result of lower muscle strength and other age-related changes to the musculoskeletal system (Karamanidis & Arampatzis, 2005). Thus, these differences in muscle architecture and activation in older compared to young athletes can influence biomechanical output while running.
Biomechanical Differences

The biomechanical differences between young and older runners have been studied extensively over the last 2 decades. A distal-to-proximal (i.e., ankle to hip) shift in peak joint extensor moments in older compared to younger adults during walking is well-documented (Cofré et al., 2011; DeVita & Hortobágyi, 2000; Judge et al., 1996). This proximal shift has also been shown in middle-aged (Paquette et al., 2021) and older runners (DeVita et al., 2016; Karamanidis et al., 2006; Kulmala et al., 2014). As previously discussed, in addition to lower muscle strength and smaller muscle size, tendon stiffness is reduced with age (Karamanidis & Arampatzis, 2005; Stenroth et al., 2012) which appears to contribute to slower muscle contraction velocity and increased time to reach peak leg press power output on a custom-made apparatus (Pearson et al., 2002). Specifically, lower plantarflexor strength (Hasson et al., 2011) and AT stiffness (Stenroth et al., 2012) may contribute to this well-established age-related distal-to-proximal shift in joint kinetics during gait. In fact, plantarflexor strength has been positively correlated with positive ankle angular work, peak propulsion GRF, and peak vertical GRF in older runners (Fukuchi et al., 2014). This suggests a relationship between age and decreased plantarflexor performance at walking, running, and sprinting speeds (Kulmala et al., 2014). Further, impact peak of the vertical GRF and instantaneous loading rate of the vertical GRF are greater in older runners compared to young runners (Bus, 2003). Although peak propulsive force was lower in older runners, they were only significant at a slower, self-selected running speed (Bus, 2003). In a different study, aging explained 15% of the variance in the reduction in horizontal propulsive force (DeVita et al., 2016). These reductions are likely related to slower running speeds in aging adults as aging results in more vertical ground reaction forces at push-off compared to younger runners (Korhonen et al., 2009). This seems reasonable, as the angle of
the net ground reaction force (the combination of horizontal and vertical GRFs) determines running speed (Bus, 2003; Korhonen et al., 2009). Given the role of plantarflexors in maintaining stride length at fast running speeds (Dorn et al., 2012), these biomechanical changes, likely mediated by muscle-tendon changes, contribute to slower running speeds and ultimately, declines in running training intensity and performance.

Plantarflexor musculature plays a crucial role in propulsion while running (Hamner et al., 2010) as peak positive ankle power is strongly correlated to step length and running speed (DeVita et al., 2016). In fact, when training distance (~48 km/week) and average pace (~5.9 min/km) are matched between young and middle-aged runners, age-related differences in ankle kinetics are not are observed while running (Paquette et al., 2018). However, young runners tend to produce more ankle positive work and peak positive power than middle-aged runners when training distance is high (~70 km/week) (Paquette et al., 2021). This investigation also indicates that by middle age (i.e., 50-70 years), there are already significant age-related changes in running biomechanics in runners. Relatedly, endurance running exposure may not be sufficient to prevent the age-related decline in tendon stiffness (Karamanidis & Arampatzis, 2005; Stenroth et al., 2016) and maximal AT force and stress (Stenroth et al., 2016) compared to young adults. All of these age-related factors appear to play a role in higher relative metabolic costs and as a result, more running effort and less enjoyment in aging runners.

Though knee joint powers may not decrease significantly with age while running, there is some evidence for lower knee angular stiffness. Lower joint stiffness for older runners at both the knee and ankle when compared to younger runners, as well as increased vertical stiffness in older runners have been observed (Kulmala et al., 2014). Joint stiffness is the slope of joint torque and angular position, calculated during the load acceptance portion of the stance phase,
and vertical stiffness is the ratio of vertical GRF to the vertical displacement of the center of mass at its lowest point (Hamill et al., 2014; Powell & Williams, 2017). Two studies found that when running, older adults have a tendency towards decreased knee range of motion (ROM) and energy absorbing ability at self-selected and set running speeds than younger runners (Bus, 2003; Fukuchi & Duarte, 2008). During treadmill running, no difference was seen in leg stiffness and vertical stiffness, but older runners had decreased leg stiffness during a rebound jump, which consisted of seven consecutive jumps attempting to maximize height each time (Pantoja et al., 2016). Findings of lower joint angular stiffness and vertical and leg stiffness in older runners suggest that age may reduce the ability to attenuate forces due to lower tendon stiffness compared to younger cohorts.

It has been suggested that distance running does not counteract age-related degeneration of MTUs because the load placed on the triceps surae MTU and quadriceps femoris (QF) MTU is not sufficient to produce measurable changes. Thus, exercise modalities other than distance running may need to be incorporated into a training program in order to sufficiently stress tendons to limit age-related changes. Incorporation of fast running or sprinting may be a good option if introduced safely and progressively. For example, when sprinting (~7.9 m/s), plantarflexor torque increases by ~11% and peak propulsive GRF by 44%, and peak ankle power generation by 51% compared to running (~4.0 m/s) in middle-aged runners (Kulmala et al., 2014). As mentioned earlier, when average running pace (~5.9 min/km) is matched between young and middle-aged runners, age-related differences in ankle kinetics are not are observed while running (Paquette et al., 2018). However, to incorporate faster running into training programs of middle-aged or older runners, tissue capacity and strength should be increased in preparation for the increased plantarflexor loads potentially to minimize injury risks. Finally, it
appears important to identify and develop training interventions for aging runners to maintain propulsive function and faster running speeds. Maintenance of propulsive function and speed would ultimately allow older runners to train at higher intensities potentially later in their lifetime.

**Resistance Training**

One possible training modality to mitigate the effects of aging via improved muscle-tendon function and propulsive biomechanical output, resistance training is an accessible option with well-documented benefits for muscular and skeletal health. When implemented appropriately, resistance training can reduce the metabolic cost of running and improve running performance. There are various forms of resistance training ranging between higher load with a lower number of repetitions (i.e., heavy resistance training) and lower load with a higher number of repetitions (i.e., endurance resistance training). These different forms of resistance training lead to the different muscle-tendon adaptations. Thus, depending on the goal of an athlete or individual, the optimal resistance training program will vary.

*Endurance Resistance Training*

Historically, endurance athletes looking to incorporate resistance training into their program have been pushed towards light, endurance focused resistance training with lower weights and 12-20 repetitions per set. In a six-week intervention, young, recreationally active participants performed the same five exercises at two different timing and intensity levels (Moro et al., 2020). The first group performed three sets of 15 repetitions of each exercise at 60% of 1RM, with 75 seconds of rest between sets. The second group performed 6 repetitions at 80% of 1RM, rested 20 seconds, lifted the same weight to failure (usually 2-3 repetitions), rested 20
seconds, and then again lifted the same weight until failure. These counted as one set, and two sets of each exercise were performed, separated by 2:30 minutes of rest. Strength measures improved for both groups, but in these recreationally active younger adults, there was a significant increase in overall body mass and lean body mass in the higher intensity group. Both groups improved their maximal aerobic power but neither group was an improvement over the other. The investigators also found that neither group decreased body fat percentage after six weeks, partially because of increased levels of reported hunger and calorie intake in the second group (Moro et al., 2020). Since these participants were not performing any additional aerobic training outside of the intervention, there was not any interference mitigating hypertrophy to avoid the significant increase in mass.

Heavy Resistance Training

All intensities of resistance training, measured as a percentage of 1RM, increase cross-sectional area of muscle and 1RM, with the largest improvements coming at higher intensities (i.e., percentages of 1RM) during training (Lasevicius et al., 2018). When controlled for volume (i.e., number of sets x number of repetitions x load), any intensity of exercise will result in muscle hypertrophy (i.e., increases in muscle mass), provided each set is continued until failure (i.e., results in more lifting volume). However, the low load or endurance (lighter weight and more repetitions) resistance training tended to result in 1RM strength (amount of load that could be moved) plateaus after six weeks, while heavy resistance (heavier weight and fewer repetitions) training continued to show strength improvements, even after 12 weeks (Lasevicius et al., 2018). It must be noted that 6 weeks may not be a long enough time period to show the effects of changes in muscle architecture due to hypertrophy, only neuromuscular adaptation in less trained individuals. In a protocol comparing heavy resistance training with plyometric
training and a third program with elements of both, all three groups showed similar improvements in strength and no practically significant changes in muscle cross-sectional area after 6 weeks of training (MacDonald et al., 2012). This indicates that the previous gains seen after endurance resistance training may only be from neuromuscular adaptation and endurance resistance training may not be as effective at also altering muscle architecture. Heavier loads induce greater improvements in 1RM than lighter loads, though both can induce improvements in strength as long as the sets are completed to failure (Schoenfeld et al., 2017). In terms of the practical implementation of the modalities for running performance, there have been many debates over the last few decades over the most optimal method of resistance training.

Plyometric Training

A recent review of studies comparing plyometric training with endurance resistance training found that plyometric training may induce similar muscle hypertrophy as endurance resistance training, but the mechanism of hypertrophy is poorly understood (Grgic et al., 2020). The authors note that older participants seem to have a lower hypertrophy response than younger participants, so the degree of hypertrophy induced by a modality may not be an important consideration for older adults. One study of younger men found that the lower endurance resistance training group had a greater increase in muscle thickness than the heavy resistance training group after 8 weeks. This may be because the endurance resistance group had to complete three times the volume of training to reach failure on each set (Schoenfeld et al., 2015). Despite that higher training volume, the heavy resistance training group showed more improvement in maximal strength measurements. It has since been established that training volume does not affect changes in maximal strength and muscle endurance, instead training volume shows a positive association with muscle hypertrophy (Schoenfeld et al., 2019). This
indicates that a lower total resistance training volume, but heavier weight will be most effective for increasing muscle strength and endurance while minimizing mass increases.

\textit{Resistance Training for Runners}

In a survey of 667 competitive runners over the age of 15 who regularly engage in strength and conditioning training, the two most common reasons for resistance training were reducing injury risk (63\% of participants) and improving performance (54\% of participants) (Blagrove et al., 2020). The most common interventions were stretching (86\%), core stability work (70\%), and resistance training (63\%). In those activities there was no difference in response based on age, sex, or level of competition. Only 35\% of runners engaged in in plyometric training, and they were disproportionately under 20 years of age and very few runners over the age of 50 incorporated this type of intervention into their training (Blagrove et al., 2020). This indicates advertising a resistance training program designed to decrease injury risk and improve performance may be an effective strategy for recruiting participants. Also, since plyometric training has not been widely studied in runners, it may be more challenging to interest runners in a training program with plyometrics unless there is strong evidence to support its inclusion.

When investigating a resistance training intervention for competitive high school aged middle- and long-distance runners, a program focusing on plyometric and free-weight resistance training found small improvements in running economy at submaximal speeds after 10 weeks of training (Blagrove, Howe, et al., 2018). Since the runners who participated in the control group spent 41\% more time running than the intervention group, resistance training may be a more efficient way to improve running economy without the stress of as many miles of running (Blagrove, Howe, et al., 2018). Although there have not been any investigations directly linking improvements in running economy with improved race performance, several have investigated
resistance-training effects on running economy. Unfortunately, many of these studies are inconsistent in terms of controlling the ongoing running training and the type of resistance training intervention attempted. Regardless of training level, the interventions focusing on complex, multi-joint movements with free weights were more likely to result in improvements in running economy (Blagrove, Howatson, et al., 2018). Since running alone is not enough to maintain ankle propulsive function, multi-joint resistance training could be time-efficient option for mitigating age-related changes in gait biomechanics.

Collegiate runners (18-24 years of age) have been a popular subject group for resistance training interventions as they usually can be recruited from a team that allows for fairly standardized running loads between participants (Barnes et al., 2013). 42 Division III collegiate cross-country runners were assigned to either heavy resistance training or a combination of heavy resistance and plyometric training for the duration (13 weeks) of their competitive cross country season. When implemented as the competitive season begins, both interventions were found to be potentially detrimental to race performance, the combination intervention more so than the heavy resistance program. Although the heavy resistance program runners showed increased leg stiffness, $\dot{V}O_2\text{max}$ and velocity at $\dot{V}O_2\text{max}$, they also had decreased running economy. The findings of this study were impacted by performing the final testing five days after the end of the season, potentially impacting motivation to maximize performance during testing (Barnes et al., 2013). In order to truly determine the effects resistance training on runners, longer implementation may be necessary.

An intervention implementing eleven weeks of lower extremity heavy resistance training for well-trained female duathletes (running and cycling) found no change in $\dot{V}O_2\text{max}$ during either sport but showed improvements in sub-maximal $\dot{V}O_2$ while cycling (Vikmoen et al., 2016,
In terms of performance, participants were able to cover more distance in both a 5 minute and 40 minute run and had higher squat and countermovement jumps compared to the control group, who had not added resistance or plyometric programming to their ongoing endurance training. This was despite increased lean mass in the lower extremity and decreased overall body mass. The investigators did not specify the age of the participants participating in this investigation (Vikmoen et al., 2016, 2017). This indicates that females can respond well to a resistance-training program in terms of performance, but changes in running economy are unclear.

Li et al. implemented heavy resistance training and heavy resistance with plyometric training interventions in male collegiate long-distance runners at the beginning of their winter training block, usually a time more focused on building a strong foundation for the late winter and spring competition season (Li et al., 2019). The runners in both groups showed improved 50 m sprint and 5 k running times after a 10-week intervention, along with improved running economy at lower speeds when compared to a control group that performed lighter load, endurance focused (lighter weight and higher repetition) resistance training. The combined training intervention group was the only intervention that also showed improved running economy at the highest speed tested (16 km·hr^{-1}) and improved performance in measures of reactive strength, indicators of increased ability to generate power, partially by increasing leg MTU stiffness. Important for distance runners, for whom increased lean mass can have detrimental effects on running economy, neither intervention incorporating heavy resistance showed an increase in lean mass or overall body mass (Li et al., 2019). This demonstrates that resistance training can affect running economy at a wide range of speeds, even if the mechanisms by which it affects running economy are not well understood.
The previous collegiate athlete studies implemented resistance training during either the primary competitive season or the offseason, but one investigation followed runners for 40 weeks, covering the offseason and the competition season (Beattie et al., 2017). Runners, collegiate and national level 1,500-10,000 m competitors who had not previously incorporated resistance training into their programming, were assigned to either a combined plyometric and heavy resistance training program or control group, which called for no additions to their previous running program. The participants reported their running training to the investigators, but otherwise continued with the normal training dictated by their individual coaches. Investigators found that again, no measures of body composition were affected by the intervention, however maximal and reactive strength and velocity at \( \dot{VO}_2 \) \( \text{max} \) all improved. These improvements came despite no change in \( \dot{VO}_2 \) \( \text{max} \) and blood lactate levels at ventilatory thresholds. The authors did not specify the gender of the participants in this investigation but did compare the \( \dot{VO}_2 \) \( \text{max} \) scores to standards for male athletes (Beattie et al., 2017). Since the percentage of \( \dot{VO}_2 \) \( \text{max} \) needed to maintain a pace is more important in middle-aged runners than absolute \( \dot{VO}_2 \) \( \text{max} \), this indicates that running economy could be improved with a combination of heavy resistance training and plyometrics.

One intervention focusing on improving plantarflexor strength in recreationally active younger adults found an 18% improvement in AT stiffness after 10 weeks of standing, explosive, isometric plantarflexor contractions timed to maximize AT stiffness (Werkhausen et al., 2018, 2019). Participants completed three training sessions per week, lasting only 40 seconds per leg, designed to minimize changes in muscle architecture (pennation angle, muscle thickness, and fascicle length). During running, the increased tendon stiffness did not decrease AT strain (relative deformation of the tendon) applied during the first part of stance phase and actually
decreased the tendon recoil (the return of stored kinetic energy as AT tension decreases). This unexpected finding may be due to limitations in the ultrasound collection method, which cannot produce clear images of tendon layers or because a lack of understanding of the relative contributions of joint angles and contractile properties of muscle to tendon length changes. So although this intervention did increase AT stiffness, it is unclear if this improves running economy or running performance (Werkhausen et al., 2018, 2019). We know that as we age, we lose muscle mass and our tendons become more compliant. Since resistance training can counteract those consequences of aging, it may be quite valuable as a strategy to decrease the effort of locomotion for older adults.

*Resistance Training for Middle-Aged Runners*

The previously discussed resistance training interventions all focused on the effects of various resistance training strategies in teenagers and adults under the age of 40. Resistance training has been well established as a strategy for slowing the rate of age-related losses in bone density and muscle volume (Fragala et al., 2019). Unfortunately, there has been limited research on specific intervention protocols for healthy adults over the age of 40. Resistance training interventions for adults over the age of 40 tend to treat them as stereotypical old people or individuals with infirmities, rather than as athletes wanting to improve their performance, regardless of age. Since resistance training can be an effective strategy for improving muscle performance in older adults and running performance in younger runners, it is likely an effective strategy for improving performance and decreasing running cost for older runners. The lower the metabolic cost of running, the more likely the individual is to continue running regularly, attenuating age-related decreases in cardiovascular fitness.
Unfortunately, studies on resistance training interventions for runners over the age of 40 are rare. Two studies on resistance training included participants with an average age of at least 40 years who engaged in some level of distance running. The first recruited 22 recreational runners (40.0±11.4 years) and included an intervention that lasted 8 weeks with two training sessions per week (Ferrauti et al., 2010). The first weekly session exercises were leg press, knee extension, knee flexion, hip extension, and ankle extension, all performed using resistance machines. Four sets of 3-5 repetitions were completed of each exercise. The second weekly session consisted of six exercises focusing on trunk muscle endurance, with participants completing three sets of 20-25 repetitions per exercise. Running (endurance training) was monitored but not controlled for 6 months prior to the resistance training study and for the 8-week duration of the intervention. Investigators found no change in spatiotemporal running variables and running economy after the intervention, despite leg flexor and extensor isometric force improvement, as measured with by strain gauges (Ferrauti et al., 2010). In considering this intervention as a model for future resistance training interventions, the authors did not focus on improving plantarflexor function, did not incorporate the complex, multi-joint exercises that would be most likely to have a positive effect on running economy, and did not control for running exposure.

The only study that specifically investigated a resistance training intervention for runners over 35 years compared a heavy resistance training intervention with a lower load, endurance focused training intervention and a control group (no resistance training) (Piacentini et al., 2013). All participants were recruited from the same running team and followed the same program of 50 km per week, made up by slow runs, interval training, and tempo runs. Both intervention groups were assigned a mix of similar, but not identical, machine and free weight upper and lower body
exercises. The heavy resistance training group completed four sets of each exercise at 85-90% of 1RM, usually 3-4 repetitions, while the traditional group completed three sets of 10 repetitions at 70% of 1RM. After the intervention, running economy at goal marathon pace improved by ~6% for the heavy resistance group, without any changes in body composition or resting metabolic rate (Piacentini et al., 2013). This finding is significant, because any improvement greater than 2.4% could be attributed to the resistance training intervention and not day-to-day variability or instrument error. However, plantarflexor function or muscle properties or AT stiffness was not evaluated to assess how the interventions specifically influence muscle-tendon characteristics.

Finally, the use of heavy resistance training shows the greatest improvement to running economy in all ages of runners. However, current evidence for resistance training in aging runners is scarce, and mechanisms to explain improvements in economy from resistance training are not well understood.

**Gaps in the Literature**

Scientists and practitioners have proposed that older runners should perform resistance training to improve musculoskeletal function and potentially improve economy. However, current evidence is scarce, and it is not clear what types of resistance training interventions may be most optimal. Lower AT stiffness may be the most important mechanism to explain lower ankle power and work generation in aging runners. Thus, measurements of tendon stiffness are crucial for understanding mechanisms behind improvements in economy from training interventions. Heavy resistance and plyometric training may be the two most effective modalities of resistance training for runners. However, plyometric training has not been well investigated despite some evidence showing improvements in running economy in younger runners and increased AT stiffness in older active adults. If implemented safely, a combination of plyometric
and resistance training could be a more efficient, effective intervention than heavy resistance training alone. Although low weight, endurance focused resistance training has been well documented as a less effective modality than heavy resistance training, it is still a common training choice for distance runners. Thus, its inclusion in a study designed to assess the most optimal types of resistance training for aging runners would be valuable and practical. A better understanding of the most optimal resistance training modalities for aging runners could help practitioners develop more effective programs to combat age-related declines in muscle-tendon properties and running performance and ultimately, keep aging runners on the roads and trails longer in life.

Research Questions

General Question

1. Does resistance training improve running economy and propulsive function while running in middle-aged runners?

Specific Questions

1. Is there an optimal resistance training intervention to improve running economy, ankle propulsive function, and AT stiffness in middle-aged runners?

2. Are the changes in ankle propulsive function and AT stiffness as a result of resistance training related to changes in running economy in older runners?
Chapter II

The Effects of Resistance Training on Running Economy and Plantarflexor Function in Middle-Aged Runners

Zoey C. Kearns, Jason R. Franz, Douglas W. Powell, Max R. Paquette

Introduction

Age-related declines in metabolic and musculoskeletal function increase the risk of physical disability, chronic disease, loss of mobility, and decreased independence (Fragala et al., 2019). Physical activity and exercise help slow the rate of decline in function in aging populations and decrease the risk of developing cardiovascular disease, cancer, neurological conditions, and respiratory infections (Lee et al., 2017). Running is a mode of exercise with a low barrier to entry whose popularity, especially in adults over 35 years (Zingg et al., 2013), has exploded over the past couple decades. The health benefits associated with running are well understood and with runners tending to have a lower resting heart rate and higher $\dot{V}O_2$ max than non-runners (Hespanhol Junior et al., 2015), to the point where it has been suggested that it has been suggested that vigorous exercisers, like marathon competitors, age at different rates than sedentary adults (Lazarus & Harridge, 2010). Although running participation can help slow the aging process, there are some inevitable age-related changes experienced by all runners.

Distance running performance is explained by a number of physiological determinants including maximal rate of oxygen consumption ($\dot{V}O_2$ max), velocity at $\dot{V}O_2$ max, blood lactate threshold, and running economy (i.e., rate of oxygen consumption at submaximal or race-specific paces) (Alvero-Cruz et al., 2020; Daniels & Daniels, 1992; Joyner, 1991; Morgan & Daniels, 1994). $\dot{V}O_2$ max declines with age (Lepers & Stapley, 2016; H. Tanaka & Seals, 2003, 2008) but...
running economy is similar between younger and older runners (Beck et al., 2016) and therefore, older runners operate at higher rates of oxygen consumption relative to $\dot{V}O_{2}\text{max}$. Although age-related metabolic changes in runners play an important role in endurance performance declines, age-related changes in muscle-tendon function (e.g., decreased tendon force, stress, and cross-sectional area) (Ebrahimi et al., 2020; Karamanidis & Arampatzis, 2006) and biomechanical output (e.g., decreased ankle power, leg, and ankle stiffness) (DeVita et al., 2016; Paquette et al., 2018, 2021; Willy & Paquette, 2019) may contribute to these declines. One of the biomechanical hallmarks of older runners is a reduction in ankle propulsive function including lower peak plantarflexor torque, positive work, and peak positive power (DeVita et al., 2016; Karamanidis & Arampatzis, 2005). These biomechanical changes are likely the result of age-related loss in muscle mass (Schneider et al., 2019), lower plantarflexor strength (Stenroth et al., 2017), and lower Achilles tendon (AT) stiffness (Karamanidis & Arampatzis, 2005; Stenroth et al., 2012). Lower AT stiffness may require more plantarflexor force (and energetic demands) and rate of force production to sufficiently shorten the muscle-tendon unit during propulsion. All of these age-related factors may contribute to higher relative metabolic costs and as a result, higher running effort and less enjoyment in aging runners. However, declines in $\dot{V}O_{2}\text{max}$ are more strongly correlated with reductions in activity level than with age (i.e., due to life changes associated with age) (Lepers & Stapley, 2016; H. Tanaka & Seals, 2008; K. Tanaka et al., 1990). Thus, it may be important to mitigate the decline of these metabolic, muscle-tendon, and biomechanical factors to slow the age-related performance declines for maintenance of running participation in older runners.

Although maintaining levels of moderate running training exposure (~48 km/week) similar to young runners may attenuate these age-related differences in ankle plantarflexor
function in middle-aged runners (DeVita et al., 2016; Paquette et al., 2018), young runners tend to produce more ankle positive work and peak positive power than middle-aged runners at similar high training exposure (~70 km/week) (Paquette et al., 2021). Relatedly, endurance running exposure may not be sufficient to prevent the age-related decline in tendon stiffness (Karamanidis & Arampatzis, 2005; Stenroth et al., 2016) and maximal AT force and stress (Stenroth et al., 2016). Therefore, it is valuable to identify interventions, beyond just running, such as resistance training that could help maintain “youthful” metabolic costs and plantarflexor function and morphological characteristics in aging runners to facilitate continued running participation.

Resistance training interventions focusing on complex multi-joint movements with free weights and heavier loads are more likely to result in improvements in running economy in distance runners (Blagrove, Howatson, et al., 2018; Rønnestad & Mujika, 2014). Relative load during resistance training is a reflection of the load as a percentage of one repetition maximum (1RM). Heavy resistance training (HRT) generally consists of loads greater than 75% of 1RM (Ferrauti et al., 2010; Li et al., 2019; Moro et al., 2020; Piacentini et al., 2013; Vikmoen et al., 2016, 2017), while light resistance training (or endurance training) typically employs loads that range between 40 to 70% of 1RM (Li et al., 2019; Moro et al., 2020; Piacentini et al., 2013). HRT alone and in combination with plyometrics exercises are both effective training strategies to improve performance and running economy in young, trained runners (Beattie et al., 2017; Li et al., 2019). Relatedly, resistance programs that combine plyometric and HRT improve maximal and reactive strength and velocity at $\dot{VO}_2\text{max}$ in young runners (Beattie et al., 2017). Further, since better plantarflexor strength tends to be concomitant with higher AT stiffness (Arampatzis et al., 2007), modalities to improve plantarflexor muscle strength should be prioritized in
distance runners. HRT improves tendon stiffness (Bohm et al., 2015). Although plyometric training may not improve plantarflexor morphology (e.g., plantarflexor muscle cross-sectional area, pennation angle, or muscle fascicle length) associated with maximal plantarflexor force production, it can improve AT stiffness in young adults (Fouré et al., 2011). However, the effects of resistance training on running performance and muscle-tendon characteristics in older runners have been studied more scarcely.

HRT in middle-aged runners has been shown to improve running economy at their marathon pace by ~6.2% while endurance resistance training did not improve running economy (Piacentini et al., 2013). Endurance resistance training is generally a less effective modality than HRT for improving muscle strength (Piacentini et al., 2013; Schoenfeld et al., 2015) and may only lead to trivial improvements in tendon stiffness (Bohm et al., 2015). Thus, HRT in combination with plyometric training may be most effective to mitigate the age-related reductions in plantarflexor strength (Stenroth et al., 2017), and AT stiffness (Karamanidis & Arampatzis, 2005; Stenroth et al., 2012). These changes in the muscle-tendon unit function could ultimately contribute to improved running economy in older runners.

The primary purpose of this study was to determine the effectiveness of heavy, heavy resistance and plyometric, and endurance resistance and plyometric training interventions to improve running economy, ankle propulsive function, and AT stiffness in middle-aged runners. We hypothesized that heavy resistance in combination with plyometrics would yield the largest improvements economy, ankle propulsive function, and AT stiffness followed by heavy resistance training and endurance resistance training with plyometrics. The secondary purpose was to determine if improvements in ankle propulsive function and AT stiffness from resistance training associated with improvements in running economy in middle-aged runners. It was
hypothesized that improvements in ankle propulsive function and AT stiffness would be positively associated with improved running economy in middle-aged runners.

**Methods**

*Participants*

Thirty-three runners between the ages of 45 and 60 years were recruited to participate in this study. Runners were able to participate if they had been running at least three times per week for an average of at least 75 minutes per week over the previous year and had not engaged in any planned lower limb resistance training more than once per week over the previous year. Additionally, participants were excluded if they have had any lower extremity surgery in the previous 2 years that would influence their capacity for training adaptations (e.g., neurological conditions) or had suffered a running-related injury that required them to stop training for more than a week in the previous 6 months. All but four of these runners had consistently been training for specific races. Prior to participation, each participant was informed of all procedures, potential risks, and benefits associated with the study through both verbal and written form in accordance with the procedures approved by the University Institutional Review Board for Human Participants Research.

*Experimental Design*

At the start of the study, all participants attended a testing session during which training information and biometric data (e.g., body mass, height) were collected (i.e., Week 1). During this session, the pre-training running economy, plantarflexor strength, AT stiffness, and spatiotemporal, ankle joint kinematic and kinetic variables during running were assessed. Following this initial testing session, participants were assigned to one of the three resistance
training groups. Groups were stratified first by age, followed by gender, weekly training duration, and lastly AT stiffness to ensure group homogeneity before the 10-week intervention (Table 1). Participants then took part in the 10-week intervention (i.e., Weeks 2 to 11) in one of three resistance training interventions: 1) heavy resistance training (HRT), 2) heavy resistance and plyometrics training (HRPT), and 3) endurance resistance and plyometrics training (ERPT). During the week following the 10\textsuperscript{th} week of the resistance training intervention (i.e., Week 12) participants returned to the laboratory for the post-training testing session.

**Table 1.** Pre-training participant characteristics and training details, and 10-week intervention training details for the heavy resistance and plyometric (HRPT) group, heavy resistance (HRT) group, and the endurance resistance and plyometric (ERPT) group (mean ± SD).

<table>
<thead>
<tr>
<th>Training Group</th>
<th>HRT</th>
<th>HRPT</th>
<th>ERPT</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size (women/men N) *</td>
<td>9 (5W/4M)</td>
<td>9 (5W/4M)</td>
<td>8 (5W/3M)</td>
<td>-</td>
</tr>
<tr>
<td>Age (years)</td>
<td>50±5</td>
<td>52±4</td>
<td>51±5</td>
<td>0.65</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>75.8±20.6</td>
<td>70.7±10.7</td>
<td>72.2±14.9</td>
<td>0.78</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.71±0.11</td>
<td>1.70±0.09</td>
<td>1.69±0.1</td>
<td>0.98</td>
</tr>
<tr>
<td>Running Experience (years)</td>
<td>16±8</td>
<td>14±7</td>
<td>13±10</td>
<td>0.73</td>
</tr>
<tr>
<td>Preferred Speed (m·s\textsuperscript{-1})</td>
<td>2.7±0.3</td>
<td>2.7±0.3</td>
<td>2.5±0.4</td>
<td>0.47</td>
</tr>
<tr>
<td>Pre-Training Weekly Running Duration (min)</td>
<td>207±98</td>
<td>214±100</td>
<td>183±85</td>
<td>0.78</td>
</tr>
<tr>
<td>Intervention Period Weekly Running Duration (min)</td>
<td>171±70</td>
<td>211±102</td>
<td>177±97</td>
<td>0.59</td>
</tr>
<tr>
<td>Intervention Adherence (% attended)</td>
<td>92.2±7.1</td>
<td>91.1±6.5</td>
<td>88.8±8.3</td>
<td>0.62</td>
</tr>
</tbody>
</table>

**Notes:** N: sample size; W: women; M: men; *: sample size varies for running economy (see results section for details), AT stiffness, and running biomechanics variables; Bold: p-value ≤ 0.05.

**Experimental Procedures**

Both testing sessions (pre- and post-training) followed identical testing procedures and were performed under the same laboratory conditions. Participants performed all testing
procedures wearing standardized footwear (NB1080, New Balance) and wore their own running shorts, shirt, and socks. A 10-camera three-dimensional (3D) motion capture system (240 Hz, Qualysis AB, Goteburg, Sweden) and an instrumented force treadmill (1200 Hz, Bertec, Columbus, OH, USA) were used to simultaneously collect kinematic and GRF data during running trials, respectively. In addition, a metabolic system (TrueOne 2400; ParvoMedics) was used to collect expired gases while running (to calculate running economy). Before experimental testing, clusters of reflective markers mounted non-collinearly on thermoplastic shells were secured on the right thigh, shank and posterior aspect of the right rearfoot. Participants then performed a five-minute running warm-up on the treadmill at their preferred speed. Participants were instructed to select the pace at which they would complete an easy run as their preferred speed. Following the warm-up, anatomical reflective markers were placed on the right femoral epicondyles, malleoli, and head of the first and fifth metatarsals as well as bilaterally on the greater trochanter of the femur and the iliac crest to define the right leg and right foot. A one-second standing calibration trial was then taken with all reflective markers to establish segment dimensions and local coordinate systems. Anatomical markers were then removed. Participants then completed two 2-minute running bouts at 1) their preferred speed (PS) and 2) preferred speed plus 5% (PS5). The difference in speeds was chosen as it would reflect an increasing demand that would be felt by the participant, while also keeping testing safe for this population. Participants were given two-minute rest breaks between each bout to ensure they were not fatigued. During these running bouts, 3D kinematic and 3D GRF data were collected for 15 seconds starting at one minute and 30 seconds.

Participants were then fitted with a rubber facemask (covering nose and mouth) connected to the metabolic cart via a plastic breathing tube. Participants completed a \( \dot{V}O_2 \text{max} \)
test on the testing treadmill using two-minute stages with increasing speed. The testing began with the participants’ preferred speed and increased by 5% every two minutes until volitional failure and confirmed with plateau in $\dot{V}O_2\max$. $\dot{V}O_2$ was collected continuously during the entire test.

Following the running test, we assessed maximal plantarflexor isometric torque and AT characteristics. To measure maximum plantarflexor isometric torque (i.e., strength), participants lay prone in an isokinetic dynamometer with knee slightly flexed and ankle at 90° in the dynamometer pedal. The foot was securely strapped to the pedal with straps to avoid movement at the ankle joint. A diagnostic ultrasound probe (MSK probe, L12-4MHz Philips, Lumify) was supported by a rigid custom 3D-printed orthotic secured around the shank with the probe centered over the gastrocnemius medialis muscle-tendon junction (MTJ). Following a standardized familiarization trials (Stenroth et al., 2012), participants then completed three trials of maximal voluntary isometric contraction (MVIC) for three seconds each separated by a one-minute rest period (Stenroth et al., 2012, 2016, 2019). During each MVIC, the longitudinal displacement of the most distal point of the gastrocnemius medialis MTJ was tracked using the diagnostic ultrasound probe.
Table 2. Overview of the three resistance training interventions.

<table>
<thead>
<tr>
<th>Intervention Groups</th>
<th>Exercises</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heavy Resistance Training (HRT)</strong></td>
<td>Front squat&lt;br&gt;Seated heel raise&lt;br&gt;Straight leg heel raises&lt;br&gt;Bent leg heel raises&lt;br&gt;Lunge&lt;br&gt;Step ups</td>
</tr>
<tr>
<td><strong>Heavy Resistance Training + Plyometrics (HRPT)</strong></td>
<td>Front squat&lt;br&gt;Box jump&lt;br&gt;Seated heel raise&lt;br&gt;Straight leg heel raises&lt;br&gt;Bent leg heel raises&lt;br&gt;Forward hop&lt;br&gt;Lunge&lt;br&gt;Countermovement jump&lt;br&gt;Step ups&lt;br&gt;Alternate leg bounds</td>
</tr>
<tr>
<td><strong>Endurance Resistance Training + Plyometrics (ERPT)</strong></td>
<td>Front squat&lt;br&gt;Box jump&lt;br&gt;Seated heel raise&lt;br&gt;Straight leg heel raises&lt;br&gt;Bent leg heel raises&lt;br&gt;Forward hop&lt;br&gt;Lunge&lt;br&gt;Countermovement jump&lt;br&gt;Step ups&lt;br&gt;Alternate leg bounds</td>
</tr>
</tbody>
</table>

Resistance Training Interventions

The focus of all three resistance training programs were lower body movements that would involve contributions from the ankle plantarflexors and apply load to the AT. All three resistance training interventions included two virtual (ZOOM) sessions per week with multiple meeting times per group. Table 2 includes the resistance training intervention exercises. The load (combination of sets and repetitions for each exercise within a workout) of each training group was matched based on AT load, a summation of scaled and normalized peak loading, loading
impulse, and loading rate, as calculated by Baxter et al. (2021). For the heavy resistance exercises, participants performed 4 sets with 5-8 repetitions and were instructed to choose a weight for which failure was expected before achieving the goal number of repetitions, with rest periods of at least one-minute between sets (Ferrauti et al., 2010; Lasevicius et al., 2018; Li et al., 2019; MacDonald et al., 2012; Piacentini et al., 2013). Between sets, participants were allowed to adjust their weight to maintain the requisite level of difficulty. For the plyometric exercises, participants performed 1-2 sets with 4-8 repetitions with rest periods of at least one-minute between sets. Finally, for the endurance exercises, participants performed 1-2 sets with 10-20 repetitions and were instructed to choose a weight for which failure was expected before achieving the goal number of repetitions with rest periods of at least one-minute between sets (Lasevicius et al., 2018; Li et al., 2019; Moro et al., 2020; Piacentini et al., 2013). All resistance training interventions began with two weeks of training focused on technique and movement skill in preparation for the more challenging demands of the heavy resistance and plyometrics training in the last eight weeks. The next eight weeks consisted of two 4-week training cycles, three weeks of progressive loading and 1 week of unloading during which participants reduced the previous week lifting load by approximately 50% (Beattie et al., 2017). Participants were instructed to maintain their typical running training during the intervention period and the researchers monitored running duration (running minutes) using a digital training log provided by the researchers (custom program, Google Sheets, Microsoft).

**Data Analyses**

Visual3D software (C-Motion, Germantown, MD) was used to process and analyze all kinematic and kinetic data. Kinematic data were interpolated using a least-squared fit of 3rd order polynomial with a three-data point fitting and maximum gap of 10 frames. Kinematic and GRF
data were filtered using a fourth-order Butterworth low-pass filter with cut-off frequencies of 8 and 40 Hz, respectively. A right-hand rule with a Cardan rotational sequence (x-y-z) was used for 3D angular computations, where x represented the sagittal plane, y represented the frontal plane, and z represented the transverse plane. A vertical GRF threshold of 20 N was used to define the start and end of the stance phase while running. Primary dependent variables included: running economy, peak plantarflexor torque, peak positive ankle power, positive ankle mechanical work, plantarflexor strength, and AT stiffness.

Running economy was calculated as the average $\dot{V}O_2$ (mL·kg$^{-1}$·min$^{-1}$) during the last 30 seconds of each running bout when steady-state at each speed was confirmed (i.e., plateau in $\dot{V}O_2$). The peak torque generated across the three plantarflexor MVIC was used to assess plantarflexor strength (Franz et al., 2019; Stenroth et al., 2012, 2017, 2019). Ankle joint angular kinematic and kinetic variables were expressed in the shank coordinate system. Newtonian inverse dynamics were used to calculate net internal joint moments normalized to body mass (Nm/kg) during the stance phase. Joint powers normalized to body mass (W/kg) were computed as the dot product of joint moments and angular velocities, and joint angular work (J/kg) was computed as the time integral of the joint angular power using the trapezoidal rule using a custom program in MATLAB (Mathworks, Natick, MA, USA). AT force was calculated by multiplying the plantarflexor MVIC torque with the externally measured lever arm of the AT (Figure 1) (Franz et al., 2019; Stenroth et al.,

![Figure 1. The externally measured lever arm of the AT is indicated in red.](image)
2012). The MTJ displacement was used to assess tendon elongation using an open-source software (version 2.2, DeepLabCut, ImageJ, NIH). This software allows for the training of a deep neural network that was used in the current study to recognize the MTJ and track its movements throughout the contraction. The network was trained on 2,764 labeled frames from 26 participants. We used a MobileNetV2-1-based neural network pre-trained on ImageNet with default parameters for 500,000 training iterations (Mathis et al., 2021). These procedures have been described in detail in previous work (Mathis et al., 2018; Nath et al., 2019) and have been validated as a reliable method to track the AT MTJ (Krupenevich et al., 2021). AT stiffness was then calculated as the slope of the AT force and the AT elongation between 10% and 80% of MVIC (Figure 2) (Stenroth et al., 2012). The average of ten steps for each running biomechanics variable, the average and peak of three trials for plantarflexor MVIC torque, the AT stiffness of one ramped MVIC trial, and running economy during the pre and post testing sessions were used in statistical analyses.

![Graphs showing the relationship between AT force and AT elongation for two different participants.](image)

Figure 2. Representative slope of the AT force and AT elongation from two different participants.

**Statistical Analyses**

A 2x3 mixed design ANOVA was used to address the primary purpose. Time served as the within-subject factor (two times points) while intervention group served as the between-subject factor (three interventions). Data normality was assessed using the Kolmogorov-Smirnov tests. If data were not normally distributed a Mann-Whitney non-parametric test was used to
compare group mean differences at each intervention time point. A one-way ANOVA was used to compare to the pre and post intervention difference in body mass. To decipher interaction effects, paired t-tests were used to compare time points and independent t-tests were used to compare groups. The 95% confidence intervals (CI) for mean differences were reported and, Cohen’s $d$ effect sizes were calculated to assess effect magnitudes using the interpretation of Hopkins (i.e., small: $d < 0.6$, moderate: $0.6 \geq d < 1.2$; large: $d \geq 1.2$) (Hopkins, 2020). Pearson’s correlation coefficient was used to assess the secondary purpose to assess the correlation between plantarflexion function (e.g., plantarflexor strength, AT stiffness, and ankle work and peak plantarflexor torque and power) and running economy. Significance level was set at an alpha level of 0.05 for all tests.

**Results**

*Participant Characteristics, Intervention Adherence, Running Training, and Dropouts*

Twenty-six participants completed both laboratory testing sessions and attended at least 80% of the resistance training sessions over the intervening 10 weeks (Table 1). From the HRT group, one participant (man) suffered an injury before the intervention began (unrelated to the experimental training), one (woman) withdrew because of muscle soreness following the first session, and one (man) withdrew after week three due to lack of time. Finally, data of one participant (man) was excluded from metabolic and biomechanical analyses due to the lack of a flight phase in testing (i.e., walking). Thus, data for eight total participants (five women) were available for analyses of the biomechanical and $\dot{VO}_2$ data for HRT and nine participants (five women) for analysis of isometric ankle data. There were no dropouts from the HRPT group, however due to instrumentation malfunctions, metabolic data were unusable for three participants (one woman) during one of the two testing sessions. Thus, data from nine
participants (five women) were available for analysis of biomechanical and isometric ankle data, and six (four women) for analysis of $\dot{V}O_2$ data for HRPT. From the ERPT group one participant (man) withdrew after week three due to illness and two participants (one woman) after weeks four and eight, respectively, due to a torn knee ligament and Achilles’ tendinopathy. One participant (woman) completed the intervention but was unavailable to attend the final laboratory testing session within two weeks of the intervention ending. Due to instrument errors during a testing session, one participant (woman) was excluded from biomechanical analyses (n = 7) leaving data for seven participants (four women) for the biomechanical analyses and data for eight participants (five women) for $\dot{V}O_2$ and isometric ankle measurement data analyses for the ERPT.

There were no significant group differences for pre-training age, body mass, height, weekly running duration, running experience, preferred easy run speed and attendance during the intervention (Table 1). The pre to post difference in body mass was also not different among the HRT (+0.6±1.0 kg), HRPT (-0.5±1.8 kg), and ERPT (-0.4±1.8 kg) groups (p = 0.25). During the training intervention participants maintained their pre-intervention weekly running duration (p=0.30). During intervention weekly duration compared to pre intervention was slightly lower for HRT (-17.8%, $d$=0.5) but unchanged for the HRPT (-1.4%, $d$=0.0) and ERPT (-3.2%, $d$=0.0). Finally, weekly running duration during the intervention was not different between group (p=0.59).

$\dot{V}O_2$max and Running Economy (RE)

There were no significant group or interaction effects for $\dot{V}O_2$max or relative and absolute RE at either speed (Table 3). We observed a main effect of time for relative RE at the preferred speed (Table 3). Relative RE improved post (82±7 %$\dot{V}O_2$max) compared to pre (84±6
%$\dot{V}O_2_{\text{max}}$) intervention (2.4%; $d=0.3$) at the preferred speed with 81% of participants improving. No time effect was observed for relative RE at the preferred +5% speed. Despite no interactions, a moderate effect size was observed for the training effect of HRPT (-4.5%; $d=0.6$) with 83% of participants improving, while small effects were observed for HRT (-2.7%; $d=0.3$) with 88% of participants improving and ERPT (-0.7%; $d=0.1$) with 63% of participants improving.

*Achilles Tendon Stiffness and Isometric Plantarflexion Torque*

Time effects but not interaction or group effects were observed for AT stiffness and isometric plantarflexor strength (Table 4). However, AT stiffness was greater post (116.3±47.9 N·mm$^{-1}$) compared to pre (92.3±44.3 N·mm$^{-1}$) intervention (26.1%, $d=0.5$) with 73% of participants showing improvement. Despite no interactions on AT stiffness, a moderate effect size was observed for the training effect of HRPT (37.4%; $d=0.8$) with 78% of participants improving, while small effects were observed for HRT (22.1%; $d=0.5$) with 67% of participants improving, and ERPT (18.0%; $d=0.4$) with 75% of participants improving. Average (28.2%, $d=0.6$) and peak (26.4%, $d=0.6$) plantarflexor strength were larger post (avg: 90.0±37.1; peak: 97.6±37.9 N·m) compared to pre (avg: 70.2±30.5; peak 77.2±32.3 N·m) intervention with 80% of participants improving in both strength measures. Despite no interactions on average plantarflexor strength, a moderate effect size was observed for the training effect of HRPT (47.0%; $d=0.8$) with 78% of participants improving, and ERPT (35.3%; $d=0.6$) with 100% of participants improving, while a small effect was observed for HRT (9.0%; $d=0.3$) with 67% of participants improving. Similar within group changes for peak plantarflexor strength were observed.
Table 3. \( \dot{V}O_2 \)max and relative (% of \( \dot{V}O_2 \)max) and absolute (mL·kg\(^{-1}\)·min\(^{-1}\)) running economy (submaximal \( \dot{V}O_2 \)) for preferred speed (PS) and PS +5% (PS5) for the heavy resistance and plyometric (HRPT) group, heavy resistance (HRT) group, and the endurance resistance and plyometric (ERPT) group (mean ± SD).

<table>
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<th>HRT</th>
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<th>p-values</th>
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<td>Pre</td>
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<td>Post</td>
</tr>
<tr>
<td>( \dot{V}O_2 )max (mL·kg(^{-1})·min(^{-1}))</td>
<td>35.1±5.4</td>
<td>36.4±5.8</td>
<td>40.0±5.9</td>
<td>39.5±7.2</td>
</tr>
<tr>
<td>PS Relative RE</td>
<td>84.8±5.1</td>
<td>82.5±8.9</td>
<td>84.5±6.3</td>
<td>80.7±7.2</td>
</tr>
<tr>
<td>PS5 Relative RE</td>
<td>89.3±4.4</td>
<td>87.8±9.3</td>
<td>88.7±5.9</td>
<td>87.3±7.6</td>
</tr>
<tr>
<td>PS Absolute RE</td>
<td>30.6±2.9</td>
<td>30.9±4.5</td>
<td>33.7±4.5</td>
<td>31.5±4.4</td>
</tr>
<tr>
<td>PS5 Absolute RE</td>
<td>32.2±3.6</td>
<td>32.8±5.0</td>
<td>35.4±5.3</td>
<td>34.2±4.6</td>
</tr>
</tbody>
</table>

Notes: Bold: p-value ≤ 0.05.

Table 4. Maximum and average isometric plantarflexion torque, and Achilles tendon (AT) stiffness during three maximal isometric ankle plantarflexion trials in an isokinetic dynamometer for the heavy resistance and plyometric (HRPT) group, heavy resistance (HRT) group, and the endurance resistance and plyometric (ERPT) group (mean ± SD).

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<tr>
<td></td>
<td>Pre</td>
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<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>Maximum Torque (N·m)</td>
<td>88.6±29.5</td>
<td>98.2±23.4</td>
<td>74.9±28.2</td>
<td>103.6±49.6</td>
</tr>
<tr>
<td>Average Torque (N·m)</td>
<td>83.6±29.5</td>
<td>91.0±22.9</td>
<td>64.7±28.2</td>
<td>95.1±48.0</td>
</tr>
<tr>
<td>AT Stiffness (N·mm(^{-1}))</td>
<td>91.3±44.3</td>
<td>111.5±42.5</td>
<td>91.3±45.2</td>
<td>125.4±44.7</td>
</tr>
</tbody>
</table>

Notes: Bold: p-value ≤ 0.05.
Running Biomechanics

There were no group, time or interaction effects for any of the joint kinetic variables (Figure 3, Figure 4, Table 5 and Table 6). Since no time effects were observed for any of the biomechanical variables at PS5, only the joint kinetics at PS are reported (see Appendix A for biomechanical variables and Appendix B for spatial-temporal variables at PS5).

Association Between Change of Ankle Mechanics and AT stiffness with RE

The Pearson correlation coefficients between change in running economy and change in AT stiffness (PS: -0.20, p=0.38, PS5: -0.07, p=0.86), peak ankle plantarflexor torque (PS: 0.33, p=0.15, PS5: 0.25, p=0.27), peak ankle positive power (PS: 0.06, p=0.80, PS5: -0.08, p=0.74), positive ankle work (PS: -0.11, p=0.64, PS5: -0.25, p=0.27), and hip to ankle positive work ratio (PS: 0.02, p=0.93, PS5: -0.5, p=0.82) were not significant (Figure 5).

Figure 3. Time series of ankle torque for the three resistance training groups before and after the intervention.
Figure 4. Time series of ankle power for the three resistance training groups before and after the intervention.

Figure 5. Pearson correlation coefficients for changes in relative running economy and changes in peak ankle plantarflexor torque, peak positive ankle power, AT stiffness, and hip to ankle positive work ratio.
Table 5. Peak ankle plantarflexor (PF) torque (Nm·kg⁻¹), peak ankle joint angular powers (W·kg⁻¹), ankle joint angular work (J·kg⁻¹), and hip to ankle positive work ratio (%) pre and post heavy resistance and plyometric (HRPT) group, heavy resistance (HRT) group, and the endurance resistance and plyometric (ERPT) group (mean ± SD) at the preferred speed.

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<tr>
<td></td>
<td>Pre</td>
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<td>Pre</td>
<td>Post</td>
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<tr>
<td>Peak Ankle PF Torque</td>
<td>-2.40±0.13</td>
<td>-2.50±0.70</td>
<td>-2.64±0.41</td>
<td>-2.56±0.23</td>
</tr>
<tr>
<td>Peak Ankle Positive Power</td>
<td>8.03±1.67</td>
<td>8.50±2.21</td>
<td>8.45±2.45</td>
<td>8.39±1.53</td>
</tr>
<tr>
<td>Peak Ankle Negative Power</td>
<td>-5.69±1.27</td>
<td>-6.08±2.02</td>
<td>-5.96±1.91</td>
<td>-5.98±1.12</td>
</tr>
<tr>
<td>Ankle Positive Work</td>
<td>0.56±0.10</td>
<td>0.58±0.21</td>
<td>0.64±0.16</td>
<td>0.59±0.14</td>
</tr>
<tr>
<td>Ankle Negative Work</td>
<td>-0.43±0.10</td>
<td>-0.44±0.16</td>
<td>-0.42±0.12</td>
<td>-0.40±0.09</td>
</tr>
<tr>
<td>Hip:Ankle Positive Work (%)</td>
<td>44.1±22.8</td>
<td>65.0±38.3</td>
<td>44.2±29.8</td>
<td>68.2±76.4</td>
</tr>
</tbody>
</table>

Notes: Hip:Ankle: percentage of positive hip relative to positive ankle work; Bold: p-value ≤ 0.05.
Table 6. Peak knee and hip joint torques (Nm·kg⁻¹), peak knee and hip joint angular powers (W·kg⁻¹), knee and hip joint angular work (J·kg⁻¹), total lower limb joint angular work (J·kg⁻¹), and spatio-temporal and ground reaction force (GRF) variables pre and post heavy resistance and plyometric (HRPT) group, heavy resistance (HRT) group, and the endurance resistance and plyometric (ERPT) group (mean ± SD) at preferred speed.

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<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
<td>Time</td>
</tr>
<tr>
<td>Peak Hip Flexor Torque</td>
<td>0.77±0.12</td>
<td>0.77±0.19</td>
<td>0.70±0.23</td>
<td>0.74±0.29</td>
<td>0.75±0.25</td>
<td>0.73±0.28</td>
<td>0.68</td>
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<tr>
<td>Peak Hip Extensor Torque</td>
<td>-1.82±0.39</td>
<td>-2.05±0.37</td>
<td>-2.11±0.64</td>
<td>-2.22±0.57</td>
<td>-1.67±0.58</td>
<td>-1.87±0.49</td>
<td>0.13</td>
</tr>
<tr>
<td>Peak Positive Hip Power</td>
<td>3.20±2.07</td>
<td>4.56±2.22</td>
<td>3.49±2.58</td>
<td>4.23±2.64</td>
<td>2.89±1.67</td>
<td>3.08±1.57</td>
<td>0.12</td>
</tr>
<tr>
<td>Peak Negative Hip Power</td>
<td>-1.42±0.78</td>
<td>-1.13±1.43</td>
<td>-1.32±0.50</td>
<td>-1.61±0.89</td>
<td>-1.23±0.77</td>
<td>-1.41±0.86</td>
<td>0.55</td>
</tr>
<tr>
<td>Positive Hip Work</td>
<td>0.24±0.14</td>
<td>0.34±0.17</td>
<td>0.29±0.24</td>
<td>0.33±0.22</td>
<td>0.27±0.21</td>
<td>0.30±0.23</td>
<td>0.27</td>
</tr>
<tr>
<td>Negative Hip Work</td>
<td>-0.12±0.05</td>
<td>-0.09±0.08</td>
<td>-0.09±0.06</td>
<td>-0.12±0.07</td>
<td>-0.14±0.11</td>
<td>-0.13±0.08</td>
<td>0.85</td>
</tr>
<tr>
<td>Peak Knee Extensor Torque</td>
<td>1.99±0.31</td>
<td>1.89±0.57</td>
<td>2.22±0.45</td>
<td>2.03±0.24</td>
<td>2.17±0.40</td>
<td>2.21±0.45</td>
<td>0.39</td>
</tr>
<tr>
<td>Peak Positive Knee Power</td>
<td>3.83±0.77</td>
<td>3.78±0.84</td>
<td>4.21±1.51</td>
<td>3.98±0.85</td>
<td>4.04±1.57</td>
<td>3.99±1.46</td>
<td>0.65</td>
</tr>
<tr>
<td>Peak Negative Knee Power</td>
<td>-7.83±1.66</td>
<td>-6.57±2.40</td>
<td>-8.42±2.23</td>
<td>-7.30±1.70</td>
<td>-7.69±0.99</td>
<td>-7.35±1.97</td>
<td>0.07</td>
</tr>
<tr>
<td>Positive Knee Work</td>
<td>0.27±0.05</td>
<td>0.25±0.10</td>
<td>0.27±0.08</td>
<td>0.25±0.07</td>
<td>0.28±0.09</td>
<td>0.30±0.10</td>
<td>0.84</td>
</tr>
<tr>
<td>Negative Knee Work</td>
<td>-0.37±0.07</td>
<td>-0.33±0.10</td>
<td>-0.40±0.11</td>
<td>-0.33±0.09</td>
<td>-0.42±0.06</td>
<td>-0.41±0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>Total Positive Work</td>
<td>1.08±0.17</td>
<td>1.17±0.34</td>
<td>1.20±0.42</td>
<td>1.17±0.26</td>
<td>1.09±0.39</td>
<td>1.18±0.23</td>
<td>0.45</td>
</tr>
<tr>
<td>Total Negative Work</td>
<td>-0.92±0.17</td>
<td>-0.86±0.19</td>
<td>-0.91±0.20</td>
<td>-0.85±0.18</td>
<td>-0.98±0.24</td>
<td>-0.96±0.26</td>
<td>0.27</td>
</tr>
<tr>
<td>Cadence (steps·min⁻¹)</td>
<td>177±9</td>
<td>176±9</td>
<td>175±10</td>
<td>176±11</td>
<td>173±10</td>
<td>167±7</td>
<td>0.20</td>
</tr>
<tr>
<td>Oscillation (m)</td>
<td>0.07±0.01</td>
<td>0.08±0.01</td>
<td>0.08±0.01</td>
<td>0.08±0.02</td>
<td>0.08±0.01</td>
<td>0.09±0.02</td>
<td>0.21</td>
</tr>
<tr>
<td>Stance Time (s)</td>
<td>0.28±0.03</td>
<td>0.28±0.04</td>
<td>0.28±0.03</td>
<td>0.28±0.03</td>
<td>0.29±0.04</td>
<td>0.30±0.04</td>
<td>0.21</td>
</tr>
<tr>
<td>Foot Contact Angle (deg)</td>
<td>7.1±15.0</td>
<td>4.3±12.5</td>
<td>4.2±9.3</td>
<td>5.9±2.6</td>
<td>1.5±12.9</td>
<td>3.2±7.2</td>
<td>0.91</td>
</tr>
<tr>
<td>Peak Propulsive GRF (BW)</td>
<td>0.21±0.03</td>
<td>0.22±0.07</td>
<td>0.23±0.06</td>
<td>0.22±0.04</td>
<td>0.20±0.05</td>
<td>0.20±0.06</td>
<td>0.72</td>
</tr>
<tr>
<td>Propulsive Impulse (BW·s)</td>
<td>0.02±0.00</td>
<td>0.02±0.01</td>
<td>0.02±0.00</td>
<td>0.02±0.00</td>
<td>0.02±0.00</td>
<td>0.02±0.00</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Notes: Foot contact angle: 3D foot segment angle in sagittal plane relative to lab coordinate; BW: body weight; Bold: p-value ≤ 0.05.
Discussion

The purpose of this study was to determine the relative effectiveness of different resistance training interventions to improve running economy, ankle propulsive function, and AT stiffness in middle-aged runners. Contrary to our hypotheses, we observed no interaction effects, but observed improved relative RE at preferred speed, greater average and peak isometric plantarflexor strength, and AT stiffness following the training. However, ankle kinetics were unchanged following resistance training. These findings suggest that resistance training focused on ankle plantarflexors, regardless of the specific type of training, improves oxygen consumption as a percentage of $\dot{V}O_2\text{max}$, isometric plantarflexor strength, and AT stiffness in middle-aged runners. [feels incomplete – like the other side of the coin is necessary to disclose?]

Despite training main effects, we observed no differences in pre to post training changes in RE, maximal isometric plantarflexion strength, or AT stiffness among the different resistance training groups. Our findings are partly supported by a previous study which reported 6.2% improvements in RE following a six-week heavy resistance training in middle-aged runners 44±5 years of age (Piacentini et al., 2013). In both studies, RE only improved at the participants’ preferred speed which was slightly slower in the current protocol 2.66±0.33 m·s⁻¹ compared to 2.99±1.3 m·s⁻¹ in Piacentini et al. (2013). However, those authors reported no improvements in RE following endurance resistance training. Importantly, they only performed paired t-tests within groups and did not use a mixed-design analysis as in the current study and therefore, did not statistically assess group differences for training effects. Further, within their endurance resistance training group, unlike in our protocol, they did not include plyometric exercises (Piacentini et al., 2013). The lack of improvement in running economy after endurance resistance training is therefore not surprising given that it omits plyometric training, which better emulates
the muscle-tendon unit demands of faster running, as well as the heavier loads needed to build additional strength. It is important however that we only observed a 0.7% improvement in RE within our ERPT group which is the smallest improvement of the three groups.

Relatedly, and in agreement with our current findings in middle-aged runners, heavy resistance training and heavy resistance training with plyometrics is consistently shown to improve RE in studies with primarily young runner cohorts (Albracht & Arampatzis, 2013; Barnes et al., 2013; Beattie et al., 2017; Li et al., 2019, 2021; Piacentini et al., 2013; Spurrs et al., 2003). No other investigation has implemented a program combining endurance resistance training with plyometrics and future studies on this modality would be useful. The only other investigation of resistance training in middle-aged runners found no improvements in RE at 2.4 and 2.8 m·s⁻¹, despite 60-minute resistance training sessions twice per week for eight weeks (Ferrauti et al., 2010). However, that study did not explicitly recruit middle-aged runners and the cohort had an average age of 40 ± 11 years suggesting that many of the participants were younger than 40 years of age and therefore, not within what we defined as middle-aged. It must be noted that the definition of chronological middle-age varies by author, and a definition of physiological middle-age has not been defined but is generally considered to be after the point at which youthful running mechanics begin to change, but while retaining the capacity to mitigate some of these age-related changes with training. Additionally, despite convincing evidence that resistance training improves RE in young runners, the training exercises used by Ferrauti et al. (2010) may not have had sufficient specificity for the mechanical demands of running. Their participants completed primarily single joint movements using machines, movements which may not be as specific for runners. A goal in developing our programs were to design programs that incorporated functional, multi-joint movements focused on the lower extremity joints most
important for generating power during running. Finally, our programs were designed to be practical for runners to perform on their own, either at home or in a gym, with minimal equipment.

Our finding of greater AT stiffness following resistance training is partially supported by previous studies. However, no other study has measured AT stiffness following resistance training in middle-aged runners. Despite no change in AT stiffness or RE after eight weeks of isometric plantarflexor training for young men (J. Fletcher et al., 2013), improvements in AT stiffness (15.8% and \(d=0.9\)) and RE (-4.2% and \(d=0.8\)) have been reported after 14 weeks of isometric plantarflexor training in young participants of unspecified gender (Albracht & Arampatzis, 2013). Changes in RE (12.9% and \(d=0.4\)) and AT stiffness (12.9% and \(d=0.7\)) were observed in young men after only six weeks of plyometric training (Spurrs et al., 2003), potentially suggesting that the length of intervention necessary to elicit changes in AT stiffness and RE may be dependent on the modality of the intervention. Further, a meta-analysis that assessed the findings of two investigations found that concurrent strength and endurance training did not increase AT stiffness in young male runners, though the change in AT stiffness did approach significance and thus, the authors suggested further investigation was warranted (Trowell et al., 2020). Finally, it must be noted that no previous investigation has measured changes in AT stiffness as an outcome measure after training in middle-aged runners, so we are adding to the evidence indicating that this is an area worthy of further study, even if we found no association between the improvements in running economy and improvements in AT stiffness.

Although we observed an improvement in RE, contrary to our hypothesis we did not observe changes in any of the ankle kinetics following the interventions, complicating our search for mechanisms explaining the improvement. A potential explanation for this discrepancy is the
use of a set speed before and after the intervention for each participant. Even though isometric plantarflexor strength improved after training, the set testing speeds may have inadvertently constrained the necessary plantarflexor mechanical demands for propulsion following training to a similar degree as during pre-testing. Middle-aged and older runners tend to exhibit a distal-to-proximal shift in joint kinetics compared to younger runners (DeVita et al., 2016; Paquette et al., 2021). We therefore expected that stronger plantarflexors and improved ankle plantarflexion function while running would lead to a greater utilization of ankle plantarflexors compared to hip extensors. However, the hip to ankle positive angular work ratio was unchanged after training. This potentially could be due to our cohort already running with youthful ankle mechanics.

When comparing our cohort’s pre-intervention peak PF torque and peak positive ankle power to young runners (average 28±7 years) tested at 2.7 m·s⁻¹, similar to our average PS of 2.66 m·s⁻¹, the middle-aged peak PF torque was slightly higher (-2.43±0.39 Nm·kg⁻¹) than the younger runners (-2.36±0.32 Nm·kg⁻¹), while peak positive ankle power was slightly lower in the middle-aged runners (7.85±2.14 W·kg⁻¹) than the younger runners (8.39±2.02 W·kg⁻¹) (Paquette et al., 2018, 2021). This comparison to young runners constrained by the same plantarflexor demands suggests that our cohort may have not needed to shift their joint strategy because they still retained youthful mechanics. Further research is warranted to better elucidate our understanding of this shift in joint kinetics, particularly focusing on what drives this shift, so we can understand why this shift happens as well as better target interventions to address it. A better understanding of the age-related distal-to-proximal shift in joint kinetics would help us understand how factors such as gender may affect age-related changes.

Our sample population included 15 women and 11 men, which make the findings generalizable across genders. Previous investigations have recruited a participant population that
is exclusively or predominantly male (Beattie et al., 2017; Ferrauti et al., 2010; J. Fletcher et al., 2010; Li et al., 2019, 2021; Piacentini et al., 2013; Spurrs et al., 2003; Trowell et al., 2021).

However, lower AT stiffness, peak AT stress and force, AT thickness, and AT cross-sectional area are observed in women compared to men in a sedentary population (Zhang et al., 2021) as well as in well-trained runners (Westh et al., 2008). While no gender-based differences in overall patellar tendon stiffness have been observed after heavy resistance training, patellar tendon stiffness increases more in young men than women lower MVIC intensities, while it increases more in women than men at higher MVIC intensities (McMahon et al., 2018). No gender-based investigations of AT response to training have been conducted, but the findings at the patellar tendon suggest there may be a similar gender-difference in tendon response to training at the AT. Since our cohort included more women than men, these gender differences in tendon characteristics and responses to training suggest that our findings may be different than previous investigations because of the predominance of women in our cohort. However, there is a lack of strength training studies with concurrent endurance training that investigate gender differences in endurance performance and adaptations (Vikmoen, 2019). Resistance training is beneficial to running economy, but these benefits may be different between genders (Barnes et al., 2013), indicating that there may be gender-based adaptations affecting real world performance outside of running economy.

Finally, we also expected improvements in RE to be, at least partly, the result of greater utilization of ankle plantarflexors and increased AT stiffness following resistance training. To assess this hypothesis, our secondary purpose was to determine if the improvement in running economy was related to changes in ankle propulsive function and AT stiffness. However, there were no associations between changes in AT stiffness or ankle kinetics and running economy
across resistance training groups. Thus, another underlying mechanism must explain the improved RE. With similar ankle joint kinetics, indicating that ankle propulsive function was unchanged following training, two potential mechanisms may explain the improved RE following training. First, the stronger plantarflexors (albeit isometrically) may suggest that plantarflexors are now able to operate at lower relative demands or require recruitment of fewer muscle fibers given that ankle propulsive function was unchanged following training. Indeed, it has been well established that lower levels of muscle fiber recruitment are associated with decreased volume of muscle activation and a lower energy cost of transport (Biewener et al., 2004; Roberts, Chen, et al., 1998; Roberts, Kram, et al., 1998). Secondly, the stiffer AT possibly improves plantarflexor tension transfer to more efficiently (i.e., fewer recruited muscle fibers) maintain plantarflexor kinetics following training (Hirayama et al., 2017). In fact, a relationship between better RE and more leg stiffness (various measures) has been widely reported (Albracht & Arampatzis, 2013; Arampatzis et al., 2006; Dalleau et al., 1998; J. Fletcher et al., 2010, 2013; Spurrs et al., 2003).

The greatest limitation of this investigation is the lack of a control group performing only running training for an equivalent amount of additional training time as the resistance training groups. It is well established that maintaining running levels and training does not provide sufficient stimulus to increase AT stiffness (Hansen et al., 2003), and multiple studies have found that control group that continues with their previous running training does not show a change in running economy or other dependent variables (Albracht & Arampatzis, 2013; Beattie et al., 2017; J. Fletcher et al., 2010; Giovanelli et al., 2017; Spurrs et al., 2003). In older runners, when divided into two groups performing identical exercises, with the heavy group performing four sets of three to four repetitions at 85-90% of one repetition maximum (1RM) and the
endurance group performing three sets of ten repetitions at 70% of 1RM, only the maximal group showed an improvement in running economy after six weeks (Piacentini et al., 2013). One strength training intervention for younger runners included a control group performing body weight exercises and stretching for an equivalent amount of time as the intervention group performed resistance and plyometric training. Although they did not find an improvement in running economy in either group, they did find that the intervention group improved their 2 km time trial time, while the control group did not (Trowell et al., 2021). This suggests that the endurance and control groups did not develop the same adaptations to strength training that improve running performance as did the heavy and intervention groups and that exercises that do not put extra load on the AT tendon will not generate sufficient force on the tendon to induce mechanical changes.

A second limitation of this intervention is the small sample size, with 22 (groups of 8, 6, and 8) participants available for metabolic analyses, 24 (groups of 8, 9, and 7) for the running biomechanics analyses, and 26 (groups of 9, 9, and 8) for isometric plantarflexor torque and AT stiffness analyses. Retaining participants over the course of a training intervention is a challenge that is reflected in the small sample sizes of previous interventions for middle aged runners, with Piacentini et al. (2013) having six participants in their HRT group and five in their endurance resistance training group, and Ferrauti et al. (2010) having eleven in their strength training group. Small participant cohorts are also common in studies evaluating AT stiffness changes after an intervention, with six and eight participants respectively in Fletcher et al. (2010) and Spurrs et al. (2003), while Albracht and Arampatzis (2013) were able to retain thirteen participants. These comparably sized cohorts indicate that although our cohort is small, it provides a novel data set of various resistance training intervention in a cohort of middle-aged runners.
Conclusion

Our results suggest that resistance training improves running economy and Achilles tendon stiffness in middle-aged, recreational runners. We present a novel finding that multiple modalities of resistance training increase AT stiffness and improve running economy at a preferred speed. This suggests that resistance training, with or without plyometrics, is an effective strategy for making running more economical for middle-aged runners.
References


Appendix A. Peak joint torques (Nm·kg⁻¹), peak angular joint powers (W·kg⁻¹), and joint angular work (J·kg⁻¹) for pre and post heavy resistance and plyometric (HRPT) group, heavy resistance (HRT) group, and the endurance resistance and plyometric (ERPT) group (mean ± SD) at preferred speed +5%.

<table>
<thead>
<tr>
<th></th>
<th>HRT</th>
<th>HRPT</th>
<th>ERPT</th>
<th>p-values</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>Peak Hip Flexor Torque</td>
<td>0.77±0.17</td>
<td>0.81±0.17</td>
<td>0.75±0.29</td>
<td>0.81±0.29</td>
</tr>
<tr>
<td>Peak Hip Extensor Torque</td>
<td>-1.91±0.37</td>
<td>-2.21±0.49</td>
<td>-2.25±0.69</td>
<td>-2.22±0.47</td>
</tr>
<tr>
<td>Peak Positive Hip Power</td>
<td>3.32±2.02</td>
<td>5.01±2.60</td>
<td>4.00±2.47</td>
<td>4.54±1.88</td>
</tr>
<tr>
<td>Peak Negative Hip Power</td>
<td>-1.55±0.72</td>
<td>-1.60±1.44</td>
<td>-1.33±0.50</td>
<td>-2.51±1.31</td>
</tr>
<tr>
<td>Positive Hip Work</td>
<td>0.25±0.14</td>
<td>0.35±0.16</td>
<td>0.30±0.20</td>
<td>0.41±0.29</td>
</tr>
<tr>
<td>Negative Hip Work</td>
<td>-0.13±0.05</td>
<td>-0.13±0.08</td>
<td>0.10±0.07</td>
<td>0.15±0.07</td>
</tr>
<tr>
<td>Peak Knee Extensor Torque</td>
<td>2.01±0.30</td>
<td>2.07±0.63</td>
<td>2.17±0.41</td>
<td>1.98±0.35</td>
</tr>
<tr>
<td>Peak Positive Knee Power</td>
<td>4.01±0.75</td>
<td>4.19±1.37</td>
<td>4.20±1.28</td>
<td>3.96±0.97</td>
</tr>
<tr>
<td>Peak Negative Knee Power</td>
<td>-8.30±1.80</td>
<td>-7.45±2.03</td>
<td>-8.88±1.40</td>
<td>-7.79±1.83</td>
</tr>
<tr>
<td>Positive Knee Work</td>
<td>0.28±0.05</td>
<td>0.26±0.09</td>
<td>0.27±0.07</td>
<td>0.27±0.05</td>
</tr>
<tr>
<td>Negative Knee Work</td>
<td>-0.38±0.09</td>
<td>-0.34±0.07</td>
<td>-0.40±0.08</td>
<td>-0.37±0.08</td>
</tr>
<tr>
<td>Peak Ankle PF Torque</td>
<td>-2.40±0.13</td>
<td>-2.54±0.62</td>
<td>-2.57±0.46</td>
<td>-2.53±0.37</td>
</tr>
<tr>
<td>Peak Ankle Positive Power</td>
<td>8.36±1.74</td>
<td>8.51±2.43</td>
<td>8.54±2.55</td>
<td>8.53±2.12</td>
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<tr>
<td>Peak Ankle Negative Power</td>
<td>-5.97±1.32</td>
<td>-5.82±1.76</td>
<td>-6.26±1.98</td>
<td>-6.11±1.18</td>
</tr>
<tr>
<td>Ankle Positive Work</td>
<td>0.57±0.11</td>
<td>0.59±0.19</td>
<td>0.62±0.14</td>
<td>0.64±0.15</td>
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<tr>
<td>Ankle Negative Work</td>
<td>-0.45±0.10</td>
<td>-0.44±0.16</td>
<td>-0.43±0.13</td>
<td>-0.43±0.06</td>
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<tr>
<td>Total Positive Work</td>
<td>1.09±0.16</td>
<td>1.20±0.30</td>
<td>1.19±0.33</td>
<td>1.32±0.35</td>
</tr>
<tr>
<td>Total Negative Work</td>
<td>-0.96±0.18</td>
<td>-0.91±0.22</td>
<td>-0.94±0.19</td>
<td>-0.96±0.10</td>
</tr>
<tr>
<td>Hip:Ankle Positive Work (%)</td>
<td>44.6±23.6</td>
<td>65.4±40.2</td>
<td>47.4±29.0</td>
<td>71.1±66.7</td>
</tr>
</tbody>
</table>

Notes: BW: body weight; Hip:Ankle: ratio of positive hip and ankle work; Bold: p-value < 0.05).
Appendix B. Spatio-temporal and ground reaction force (GRF) variables pre and post heavy resistance and plyometric (HRPT) group, heavy resistance (HRT) group, and the endurance resistance and plyometric (ERPT) group (mean ± SD) at preferred speed +5%.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>Cadence (steps·min⁻¹)</td>
<td>179±9</td>
<td>179±9</td>
<td>176±11</td>
<td>179±10</td>
</tr>
<tr>
<td>Oscillation (m)</td>
<td>0.08±0.01</td>
<td>0.07±0.01</td>
<td>0.08±0.01</td>
<td>0.08±0.01</td>
</tr>
<tr>
<td>Stance Time (s)</td>
<td>0.27±0.03</td>
<td>0.28±0.03</td>
<td>0.27±0.03</td>
<td>0.27±0.02</td>
</tr>
<tr>
<td>Foot Contact Angle (deg)</td>
<td>7.1±14.5</td>
<td>7.8±7.4</td>
<td>5.7±10.8</td>
<td>5.2±3.0</td>
</tr>
<tr>
<td>Peak Propulsive GRF (BW)</td>
<td>0.22±0.03</td>
<td>0.24±0.08</td>
<td>0.24±0.06</td>
<td>0.23±0.05</td>
</tr>
<tr>
<td>Propulsive Impulse (BW·s)</td>
<td>0.02±0.00</td>
<td>0.02±0.01</td>
<td>0.02±0.00</td>
<td>0.02±0.00</td>
</tr>
</tbody>
</table>

Notes: Foot contact angle: 3D foot segment angle in sagittal plane relative to lab coordinate; BW: body weight; Bold: p-value ≤ 0.05.