THE EFFECTS OF BICYCLING EXERCISE ON THE METABOLIC COST OF WALKING IN OLDER ADULTS

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ABSTRACT

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Impaired walking performance is a key determinant of morbidity among older adults. A distinctive characteristic of impaired walking performance among older adults is a greater metabolic cost compared to young adults. Specifically, healthy older adults have been shown to have a 15-20% greater metabolic cost of walking compared to young adults. However, a recent study suggests that older adults who routinely run for exercise have a lower metabolic cost of walking compared to older adults who walk for exercise. Yet, it remains unclear if other aerobic exercises such as bicycling elicits similar improvements on walking metabolic cost among older adults. The purpose of this study was to determine if regular bicycling exercise affects metabolic cost of walking in older adults. We measured metabolic rate while 33 older adults "bicyclists" or "walkers" and 16 young adults walked on a level treadmill at four speeds between (0.75-1.75 m/s). We compared metabolic cost in the three groups. Across the range of walking speeds, older bicyclists had a 9-17% lower metabolic cost of walking compared to older walkers ($p=.009$) and similar metabolic cost of walking compared to young adults ($p=1.00$). In conclusion, bicycling exercise mitigates the age-related deterioration of walking metabolic cost, whereas walking for exercise appears to have a minimal effect on

improving metabolic cost of walking in older adults. We suspect the greater aerobic intensity of bicycling exercise may maintain muscle mitochondrial efficiency in aging and thus helps explain the lower metabolic cost of walking in older bicyclists versus older walkers.

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INTRODUCTION

Impaired walking performance is a key determinant of morbidity among older adults (43). Around the age of 65 years a decline in walking performance begins to occur. A subtle but noticeable impairment that has been observed is an increased metabolic cost of walking (lower economy) in older adults (30). Healthy older adults have been shown to have a 15-20% greater metabolic cost during walking, across all tested speeds and incline grades in comparison to young adults (27). Approximately 20% of United States' citizens will be over the age of 65 by the year 2030. As the percentage of adults over the age of 65 continues to grow, the obligation for mitigating age-related deteriorations in mobility will continue to become a key element of preventative health care.

However, age alone is a less accurate predictor of mortality than overall health and fitness (43). Beck et al. (33) showed that older adults who consistently run for exercise have a considerably lower metabolic cost of walking relative to average healthy older adults (43). Their findings suggest that consistent running can reduce early onset of fatigue while walking and improve functional independence later in life. Interestingly, the same study showed that older adults who walk for exercise do not yield similar improvements in walking performance. However, other studies that implemented vigorous walking interventions showed a reduction in metabolic cost of walking, contrarily, more moderate exercise interventions did not yield improvements in walking energetics (25, 29, 44). These different results may be due to the intensity of the exercises prescribed; vigorous aerobic exercise may improve metabolic cost more than other forms of exercise (33). Yet, it remains unclear if other forms of aerobic exercises have a similar effect as running on the metabolic cost of walking in older adults.

Walking is an effective and essential human motor task, necessary for activities of daily living. While walking, over 200 muscles generate forces by consuming metabolic energy to perform the mechanical work, support the weight of the body, laterally stabilize the body and swing the leg forward (18, 36-38). These are considered the four main determinants of the metabolic cost of walking. Out of these main determinants, supporting the body and performing mechanical work to accelerate the body account for ~80% of the metabolic cost of walking: 30% and 50% respectively (5, 32). Researchers that have looked at age-related biomechanical differences of walking found that older adults are performing nearly equal or even less mechanical work as young adults (30, 36) and have a similar ability to conserve mechanical energy via an inverted pendulum exchange of kinetic and potential energy (37). Ortega and Farley (36) also found that, while older adults perform a similar amount of mechanical work as young adults, they perform that work using a lower muscular efficiency. A more recent study found that older runners who consume less metabolic energy for walking have similar biomechanics as older walkers, who are less aerobically trained. (33). These studies suggest that similar biomechanical determinants underlie the metabolic cost of walking across the span of life, and that the improvements in walking economy (lower metabolic cost) associated with running exercise are likely due, not to changes in the mechanics of walking, but to other factors that contribute to the metabolic cost of walking, such as muscle co-activation and or impaired muscular efficiency.

Over the past decade several studies have shown that older adults co-activate antagonist muscles 30-50% more than young adults when walking on level and uphill slopes (35, 41). It has been hypothesized that the increased co-activation of antagonist muscle may be a strategy for increasing joint stability and ultimately to reduce the risk of falling. While increased co-activation must certainly increase metabolic energy consumption, the co-activation of antagonist muscles in older adults is only moderately correlated with a higher metabolic cost of walking (22, 41). Thus, co-activation may be a contributor to the increased metabolic cost of walking in older adults, but is unlikely to be the main factor that explains the 15-20% increased metabolic cost. It remains unclear if older adults who have a lower metabolic cost of walking (such as older runners) also have a decreased amount of co-activation of the antagonist muscles. However, changes in muscular efficiency is a more likely explanation for the 15-20% increased metabolic cost observed.

The metabolic cost of walking has been shown to be directly associated with muscular efficiency (34). Muscular efficiency is the ability of muscle to utilize oxygen and chemical energy to produce mechanical work. Muscular efficiency is the product of contractile coupling efficiency and mitochondrial coupling efficiency (17). Contractile coupling efficiency refers to the amount of ATP that is required to perform a muscle contraction. Recent studies show that older adults have a similar contractile coupling efficiency to young adults, regardless of fitness levels (9). Selective sarcopenia of type II muscle fibers occurs with aging, starting around the age of 50, but increases in the 6th decade, increasing the relative percentage of type I muscle fibers (12). Type I muscle fibers are considered to have a better contractile coupling efficiency in comparison to type II muscle fibers (11); thus it has been argued that increased percentage of type I muscle fibers leads to a decrease in metabolic cost of exercise (46). However, most research shows an increased metabolic cost of exercise in older adults (27, 30, 36). This discrepancy between hypothesis and reality may be because contractile coupling efficiency stays relatively consistent between older and young adults, while a 30-50% decrease in mitochondrial coupling efficiency is shown to occur in older adults (1, 9).

Studies show untrained healthy older adults have a reduced mitochondrial coupling efficiency compared to young adults (1). Mitochondrial coupling efficiency refers to the amount of oxygen required to create ATP. 25% of mitochondria content is lost with aging due to sarcopenia, but it has also been shown that 30% of the mitochondria that is still functional is less efficient at synthesizing ATP (7). It is believed that with normal aging, mitochondrial coupling efficiency declines as a result of reactive oxygen species breaking down the inner mitochondrial membrane and/or impairing the electron transport chain; as a result, the mitochondria must take in more oxygen to create the same amount of ATP (lower ATP/O_2) (1). Although mitochondrial coupling efficiency appears to decline with normal aging, Conley et al. (9) observed that a 6-month exercise intervention improves mitochondrial coupling efficiency among older adults. Moreover, Coen et al. (6) showed that older adults who have higher mitochondrial coupling efficiency have a faster preferred walking speed and higher aerobic capacities. These studies suggest that aerobic exercise may have the potential to ameliorate mitochondrial dysfunction and therefore lower the metabolic cost of exercise.

Older adults over the age of 65 have a high prevalence of osteoarthritis and osteoporosis (26). One in four women and one in ten men over the age of 65 are diagnosed with osteoporosis, while it is estimated 25% of people over the age of 55 in the United Kingdom have chronic knee pain (39). Consequently, a decline in activities of daily living and an increase in metabolic cost can occur if older adults with degenerative bone and joint diseases do not stay active. To keep older adults with knee pain active, but not exacerbate the pain, the most common form of exercise prescribed is general walking. Since walking may not mitigate the onset of an increased metabolic cost, more vigorous running would be a more beneficial prescribed exercise, except that it may contribute to knee pain and symptoms of arthritis. In running, the body experiences vertical impact loads as great as 2-5 times body weight. Moreover, novice runners may run with improper form that alters running mechanics, leading to increased acute and chronic injury (3, 14). Among older adults, these forces may increase pain in the joints and lead to a decline in exercise adherence. Alternatively in bicycling exercise, forces applied to joints are less than that of running and more comparable to the amount of force applied to joints while walking (16). Bicycling can also be performed at a high aerobic exercise intensity with a low weight-bearing impact that can potentially be a safe alternative to decrease the metabolic cost of walking.

Older bicyclists have been shown to have a lower metabolic cost of cycling compared to untrained young adults and older sedentary adults (20, 40, 42). These studies suggest that participation in regular bicycling exercise may be similar to running exercise in that it may help to prevent normal age-related declines in muscular efficiency.

The purpose of this study is to determine if regular bicycling exercise affects walking metabolic cost in older adults. We hypothesize that older bicyclists will have a lower metabolic cost of walking compared to older walkers and a similar metabolic cost of walking to healthy young adults.

Delimitations

1. The Study was delimited to 60 healthy participants (20 young adults, 20 older walkers and 20 older cyclists) with no known neurological, orthopedic or cardiovascular disease.
2. The study only included participants from Humboldt County, California and thus may not represent older adults from other parts of California or the United States.
3. Measurements of walking energetics (metabolic cost) and kinematics were only taken at four speeds and may not be representative of all walking speeds.

Assumptions

1. Participants did not partake in physical activity for one day prior to data collection.
2. All participants had similar gait mechanics when walking on the treadmill as suggested by several prior studies.
3. There are no gender differences in walking energetics and mechanics as suggested by several prior studies.
4. All participants truthfully self-reported medical history and exercise routine.

5. Measurements of metabolic cost accurately predicted sub-maximal steady-state metabolic energy of all participants.

Operational definitions

1. **Metabolic Cost of Walking:** the amount of metabolic energy used during walking exercise. This can be calculated via the oxygen consumed and carbon dioxide expelled during the steady state portion of a work rate. Synonym- metabolic power, walking economy and walking efficiency.
2. **Gross Metabolic Power (Watt/kg):** The rate of metabolic energy consumption normalized to body mass. Synonym- gross metabolic cost.
3. **Resting Metabolic Power:** The rate of metabolic energy consumption during quiet standing.
4. **Net Metabolic Power:** The rate of metabolic energy consumption required for an exercise such as walking calculated by subtracting resting metabolic power from the gross metabolic power. Net metabolic power is an ideal way to determine energy expenditure at a given work rate while accounting for the fact that people may have different resting metabolic rates.
5. **Net Cost of Transport:** Net metabolic power divided by walking speed (m/s) to determine energy expenditure per distance traveled.
6. **Healthy:** No major neurological, orthopedic, or cardiovascular disorders
7. **Young:** 18-35 years of age
8. **Older:** 65+ years of age

9. **Bicyclists**: Bicycle ≥30 minutes, 3×/week (or the equivalent)

10. **Walkers:** Walk ≥30 minutes, 3×/week (or the equivalent)

MATERIALS AND METHODS

Subjects

Forty nine healthy participants were recruited from the local county, including, 16 young adults (9 Male, 7 Female), 16 healthy older walkers (7 Male, 9 Female) and 17 healthy older walkers who bicycle for exercise (13 Male, 4 Female). Table 1. encapsulates subjects' anthropometric characteristics. Older adults recruited were a minimum of 65 years of age with no self-reported walking impairments in agreement with previous studies. Young adults were aged 18-35 with no self-reported walking impairments. All subjects were free of major neurological, cardiovascular and orthopedic problems. Older bicyclists self-reported bicycling for exercise a minimum of 30 minutes a day 3 times a week. Older walkers self-reported walking for exercise a minimum of 30 minutes a day 3 times a week. All subjects gave written informed consent prior to participation of the study. The Humboldt State University Institutional Review Board approved this protocol prior to any subject participation.

Protocol

Subjects completed two sessions. Prior to the first session, subjects underwent a brief medical and exercise screening. For all qualified participants, the first session consisted of informed consent, a more in-depth medical screening, and subject familiarization to treadmill walking for six minutes at four speeds (0.75, 1.25, 1.60, and

1.75m/s). This familiarization period exceeded the recommended minimum treadmill habituation time of 10 minutes (45, 47).

Following a minimum of three days' rest and at the start of the second session, we measured each participant's anthropometrics (height, mass, leg length). We then measured resting metabolic rate as each subject stands quietly for six minutes. For the experimental trials, participants walked at each of the four speeds (0.75, 1.25, 1.60, and 1.75m/s) separated by at least five minutes of rest. Within the last three minutes of each six minute trial, we collected data to determine stride frequency/ length, heart rate and the rate of O_2 consumption and CO_2 production.

Metabolic cost

Using open circuit expired gas analysis system, we measured oxygen consumption $\dot{V}O_2$ (mlO_2/min) and carbon dioxide expiration $\dot{V}CO_2$ ($mlCO_2$/min). To make sure oxidative metabolism was the main pathway, the collected data was from the last 2-3 minutes of each trial to ensure respiratory exchange rate (RER) reached a steady state and stayed below 1.0 (2). We then subtracted resting standing metabolic power from exercise gross metabolic power to determine net metabolic power. Net metabolic power is the rate of metabolic power consumed at a given exercise intensity (W/kg) factoring out resting basal metabolic rate. Net cost of transport (Net CoT) was determined by taking net metabolic power and dividing by the speed to determine energy cost per unit traveled.

Stride kinematics

In the last minute at each walking speed we counted how long it takes to complete 20 strides to determine stride frequency (Hz). Using the treadmill speed and measured stride frequency, we calculated stride length using the formula…

$$Stride\ Length\ (m) = \frac{Speed\ (\frac{m}{s})}{Stride\ Frequency\ (Hz)} \quad (1)$$

Statistical analyses

We used repeated-measure analysis of variance (ANOVA, p<.05) to determine statistical differences among groups (older bicyclists vs. older walkers vs. young adults). When appropriate, we applied independent t-tests to determine differences between older bicyclists, older walkers, and young adults at each speed. We used SPSS software for these tests (SPSS Inc., Chicago, IL). All data was reported as mean ± SEM unless otherwise specified.

RESULTS

In support of our hypothesis older bicyclists had a 9-17% lower net metabolic cost of walking compared to older walkers, across a range of level walking speeds ($p=.028$; Fig. 1). Moreover, when compared to young adults, older bicyclists consumed a similar amount of metabolic energy for walking across the range of speeds ($p=1.000$). At the slowest speed of 0.75m/s, older bicyclists consumed a similar amount of metabolic energy as older walkers ($p=.231$) and was ~16% greater than energy consumed by young adults ($p=.011$). However, at the three fastest speeds (1.25, 1.6 and 1.75 m/s) older bicyclists consumed 14-17% less metabolic energy for walking compared to the older walkers ($p<.01$) and a similar amount of metabolic energy as young adults ($p>.05$). For all groups, there was a linear increase of net metabolic cost from the slowest speed to the fastest speed for all groups ($p<.0001$).

In agreement with previous studies, older walkers consumed metabolic energy for walking at an 11-24% faster rate compared to young adults ($p=.006$). Post hoc tests indicate that that a difference in metabolic cost of walking between young adults and older walkers existed at each speed, two older walkers were unable to complete the 1.75 m/s walking trial due to fatigue and the vigorous nature of the speed.

In this study we also measured the fundamental stride kinematics of stride length and frequency which are inversely related at each speed. We observed that older bicyclist used a 5% longer stride length and thus slower stride frequency compared to older walkers ($p=.046$) and a similar stride length/stride frequency as young adults ($p=1.00$).

DISCUSSION

In this study, we investigated the effect of bicycling and walking for exercise on the metabolic cost of walking in older adults. In support of our initial hypothesis, older bicyclists consumed less metabolic energy for walking compared to older walkers and a similar amount of metabolic energy as young adults. Furthermore, older walkers consumed an average of 16% more metabolic energy for walking compared to young adults.

Although the older walkers consumed more metabolic energy for walking than the older bicyclists, older walkers took shorter strides across the range of speeds. Given that stride length kinematics in the present study was shorter for older walkers, older walkers should be performing slightly less external mechanical work; which would not explain their higher metabolic energy consumption (13). In agreement with prior research, average older adults have been shown to take shorter strides compared to young adults and active older adults. Results of prior research also suggest little difference in walking kinetics between young and older adults (33, 36). It is likely that other, non-biomechanical factors underlie the lower metabolic cost of walking observed in older bicyclists (13, 36-38). Across the range of speeds tested, older bicyclists as well as young adults and older walkers minimized their net cost of transport at intermediate speeds close to 1.25 m/s. This well characterized U-shaped relation between cost of transport and speed further suggests that biomechanical factors such as external and internal mechanical work and the inverted pendulum exchange of mechanical energy are similar between these groups (27, 33, 36). Thus, our results are in agreement with prior studies showing that active healthy older adults use similar biomechanics of walking, and suggest that the higher metabolic cost in older walkers is likely due to other internal factors, such as declines in muscle efficiency and/or increased co-activation of the antagonist muscle (1, 35, 37, 41).

In many studies, older adults (over the age 65 years) have been shown to consume an average 15-20% more metabolic energy for walking than young adults (27, 36). However, the influence of participating in an active lifestyle on this increased cost of walking is unclear. For example, Martin et al. (27) found that both sedentary and active older adults who participate in regular physical activity (primarily aerobic) for 45 minutes, three times per week consume more metabolic energy for walking than young adults. Similarly, Ortega and Farley (35) showed that older adults who specifically walk for exercise 45 minutes, three times per week also exhibited a greater metabolic cost and reduced mechanical efficiency during walking compared to healthy young adults. However, in recent a study by Thomas et al. (44), it was shown that participating in vigorous waking exercise could reduce the metabolic cost of walking in older adults. Based on the conflicting results of these studies, it seems possible that the beneficial effect of aerobic exercise on the metabolic cost of walking in older adults is intensity related, rather than task related. This hypothesis was substantiated by Ortega et al.'s (33) findings that older runners consumed ~15% less metabolic energy for walking compared to older walkers. Similar to the older runners in Ortega et al. (33), our study shows that older bicyclists consume less metabolic energy than older walkers and a similar amount as young adults particularly at the moderate to fast walking speeds.

Prior research suggests that older adults consume more metabolic energy for walking in part as a result of reduced muscular efficiency related to impaired mitochondrial function (6, 35). As humans advance in age, mitochondria become damaged from the cumulative effect of reactive oxygen species generation. These reactive oxygen species may damage the inner mitochondria membrane, increasing the amount of H^+ leaking across the membrane and lowering mitochondrial coupling efficiency (lower ratio of ATP to O_2) (1, 7, 8) thus, reducing muscular efficiency. While a reduction in muscular efficiency associated with mitochondrial uncoupling may increase the cost of walking in older adults (8, 34), recent evidence suggests that vigorous aerobic exercise may help to repair this oxidative damage by increasing mitochondrial protein turnover within the muscle cell (10, 23, 31), improving muscular efficiency (9, 23) and therefore, reducing the cost of walking. Factors contributing to the increased metabolic cost of walking in older adults may be more malleable than previously believed and therefore explain the improvements of the metabolic cost of walking we see among older bicyclists (6, 7).

Another possible contributor to the greater cost of walking in older adults is increased co-activation of antagonist muscles. Several prior studies have shown that older adults, including sedentary and active walkers, co-activate antagonist lower limb muscles particularly in the muscles spanning the thigh (hamstrings and quadriceps) more than young adults. It has been hypothesized that the increased antagonist leg muscle co-activation helps stabilize the legs and improve dynamic stability (21, 41). However, because co-activation of antagonist muscles is only moderately correlated to the metabolic cost of walking in older adults (35), it is likely that the increase in energy consumed due to co-activation, is not the main contributor to the greater cost of walking typically observed in older adults. Interestingly, Häkkinen et al. (19) found that resistance training can decrease the amount of co-activation in older adults. Therefore, it seems possible that maintaining an active lifestyle through activities such as vigorous walking, running or bicycling maintains muscle strength, and reduces antagonist muscle co-activation.

Unexpectedly, older bicyclists and older walkers consumed a similar amount of metabolic energy at the slowest walking speed of 0.75 m/s. It is unclear why older bicyclists did not yield improvements to their metabolic energy consumption at the slowest walking speed but did at the faster walking speeds; a potential reason may be due to the lower amount of muscle fiber recruitment needed to perform at the lower work rate (28). If there are fewer of the more efficient muscle fibers being used, there will be less evidence of an improved walking economy at slower speeds. However, Ortega et al. (33) found that older runners had improved walking economy at the same slower speed compared to older walkers, suggesting that this possible mechanism does not fully explain why older bicyclist have a similar cost of walking at the slowest speed of 0.75 m/s. Another possibility may be that these efficiency adaptations are intensity specific, since bicyclists tend to pedal at fast cadences (42), it is only at similar fast walking speed cadences that their mitochondria are more efficient at converting oxygen into ATP. Or perhaps, since it has been shown that dynamic stability is improved at slower walking speeds (15), older bicyclists and walkers are more likely to activate antagonist muscles, explaining the better stability, yet decreasing their walking economy. However, these unexpected results emphasize that there is still a lot unknown about the interaction exercise has on the metabolic cost of walking in older adults.

Yet, without aerobic exercise, aging muscles will not properly maintain and repair themselves, leading to a progression of further physiological declines (4) and higher metabolic costs of walking (27). Unfortunately, when older adult use more energy to perform a walking task, they may be less inclined to walk as much or participate in other physical activities. The increased metabolic cost of walking, may predict and indirectly contribute to an increased risk of degenerative diseases and declines in activities of daily living that occur in the last 15% of life (43). The results of this study as well as prior studies, suggest that participation in vigorous aerobic exercise, such as running or bicycling, may help improve or maintain muscle efficiency and walking economy in older adults. While running is a wonderful exercise for maintaining or even improving cardiovascular, bone and muscle health (24), many older adults with existing orthopedic conditions, such as joint arthritis, may not be able to participate without pain, due to the large forces experienced by the body during running exercise (3, 14). However, many older adults may be able to achieve similar health benefits from less impactful yet vigorous bicycling exercise; (16) a non-weight bearing aerobic exercise that can be done indoors, outdoors, recumbently or upright. Our results suggest that if performed consistently, bicycling can improve walking economy, thus likely improving mobility and the ability to achieve activities of daily living. Regardless of which aerobic exercise a person chooses, the body of literature which this study contributes to clearly suggests that it is imperative to stay active throughout life, to help maintain health and mobility.

Limitations

A limitation of the study is that all exercise routines were self-reported and that the exercises we were most concerned with were frequent walking and bicycling. We did not exclude any subject if they added other activities such as strength training to their life style. We understand that the addition of exercises can potentially alter the results of metabolic cost. Yet, it would have been extremely difficult to recruit participants if we delimited the study to people who did not do any other activities besides bicycling or walking. Nonetheless, we delimited the study to make bicycling or walking the main form of aerobic exercise participants frequently partook in. Due to the previous studies looking at exercise interventions effect on the metabolic cost of walking, we assume that higher intensity aerobic exercise is what affects the metabolic cost of walking more than other less aerobically intense forms of exercise (33, 44).

Future studies

We have quantified the differences of metabolic cost of walking between older walkers and older bicyclists. The similarities in the metabolic cost of walking between older bicyclists and older runner's gives strong evidence that aerobic exercise has a profound effect on the metabolic cost of walking. Moreover, the aerobically trained older adults do not just have a lower metabolic cost of walking compared to their sedentary and walking counter parts, but their metabolic cost of walking more closely resembles that of a young adult. What we did not discover in this study is the “why” and the “how”. Why does the average older adult use more energy to walk the same distance as a young adult? And how does aerobic exercise lower the metabolic cost of walking in older adults? Future research should look at differences of co-activation during walking between aerobically trained and untrained older adults, as well as correlations of mitochondrial coupling efficiency and the metabolic cost of walking. Although we identified that bicycling for exercise is more beneficial to the metabolic cost of walking than walking itself is; from a practitioner’s standpoint, it would be useful to prescribe exact intensity and frequencies of exercise to benefit the metabolic cost of walking for older adults. It may be that swimming and more vigorous walking, such as hiking, can also be prescribed to older adults who want to lower their metabolic cost of walking and maintain a healthy lifestyle.

Conclusion

In conclusion, bicycling for exercise maintains a more youthful metabolic cost of walking in older adults. However, the normal age-related decline in walking economy still exists in older walkers. It is likely that factors that affect metabolic energy consumption in muscle such as muscular efficiency and antagonist muscle co-activation may be improved by participation in vigorous aerobic exercise and therefore, explain the improved walking economy observed in older bicyclists.

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GRANTS

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REFERENCES

1. **Amara CE, Shankland EG, Jubrias SA, Marcinek DJ, Kushmerick MJ, and Conley KE**. Mild mitochondrial uncoupling impacts cellular aging in human muscles in vivo. *Proc Natl Acad Sci U S A* 104: 1057-1062, 2007.
2. **Brockway J**. Derivation of formulae used to calculate energy expenditure in man. *Human nutrition Clinical nutrition* 41: 463-471, 1987.
3. **Buist I, Bredeweg SW, Bessem B, Van Mechelen W, Lemmink KA, and Diercks RL**. Incidence and risk factors of running-related injuries during preparation for a 4-mile recreational running event. *British journal of sports medicine* 44: 598-604, 2010.
4. **Carmeli E, Coleman R, and Reznick AZ**. The biochemistry of aging muscle. *Experimental gerontology* 37: 477-489, 2002.
5. **Cavagna G, Franzetti P, and Fuchimoto T**. The mechanics of walking in children. *The Journal of Physiology* 343: 323, 1983.
6. **Coen PM, Jubrias SA, Distefano G, Amati F, Mackey DC, Glynn NW, Manini TM, Wohlgemuth SE, Leeuwenburgh C, Cummings SR, Newman AB, Ferrucci L, Toledo FG, Shankland E, Conley KE, and Goodpaster BH**. Skeletal muscle mitochondrial energetics are associated with maximal aerobic capacity and walking speed in older adults. *J Gerontol A Biol Sci Med Sci* 68: 447-455, 2013.
7. **Conley KE, Jubrias SA, Amara CE, and Marcinek DJ**. Mitochondrial dysfunction: impact on exercise performance and cellular aging. *Exercise and sport sciences reviews* 35: 43-49, 2007.
8. **Conley KE, Jubrias SA, Cress ME, and Esselman P**. Exercise efficiency is reduced by mitochondrial uncoupling in the elderly. *Experimental physiology* 98: 768-777, 2013.
9. **Conley KE, Jubrias SA, Cress ME, and Esselman PC**. Elevated energy coupling and aerobic capacity improves exercise performance in endurance-trained elderly subjects. *Exp Physiol* 98: 899-907, 2013.
10. **Conley KE, Jubrias SA, and Esselman PC**. Oxidative capacity and ageing in human muscle. *The Journal of Physiology* 526: 203-210, 2000.
11. **Coyle EF, Sidossis LS, Horowitz JF, and Beltz JD**. Cycling efficiency is related to the percentage of type I muscle fibers. *Medicine and science in sports and exercise* 24: 782-788, 1992.
12. **Deschenes MR**. Effects of aging on muscle fibre type and size. *Sports Medicine* 34: 809-824, 2004.
13. **DeVita P, and Hortobagyi T**. Age causes a redistribution of joint torques and powers during gait. *J Appl Physiol (1985)* 88: 1804-1811, 2000.
14. **Dugan SA, and Bhat KP**. Biomechanics and analysis of running gait. *Physical medicine and rehabilitation clinics of North America* 16: 603-621, 2005.
15. **England SA, and Granata KP**. The influence of gait speed on local dynamic stability of walking. *Gait & posture* 25: 172-178, 2007.

16. **Ericson MO, and Nisell R**. Patellofemoral joint forces during ergometric cycling. *Physical therapy* 67: 1365-1369, 1987.
17. **Gaesser GA, and Brooks GA**. Muscular efficiency during steady-rate exercise: effects of speed and work rate. *Journal of applied physiology* 38: 1132-1139, 1975.
18. **Gottschall JS, and Kram R**. Energy cost and muscular activity required for leg swing during walking. *J Appl Physiol (1985)* 99: 23-30, 2005.
19. **Häkkinen K, Kallinen M, Izquierdo M, Jokelainen K, Lassila H, Mälkiä E, Kraemer W, Newton R, and Alen M**. Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *Journal of Applied Physiology* 84: 1341-1349, 1998.
20. **Hopker JG, Coleman DA, Gregson HC, Jobson SA, Von der Haar T, Wiles J, and Passfield L**. The influence of training status, age, and muscle fiber type on cycling efficiency and endurance performance. *Journal of Applied Physiology* 115: 723-729, 2013.
21. **Hortobágyi T, and DeVita P**. Muscle pre-and coactivity during downward stepping are associated with leg stiffness in aging. *Journal of Electromyography and Kinesiology* 10: 117-126, 2000.
22. **Hortobagyi T, Finch A, Solnik S, Rider P, and DeVita P**. Association between muscle activation and metabolic cost of walking in young and old adults. *J Gerontol A Biol Sci Med Sci* 66: 541-547, 2011.
23. **Jubrias SA, Esselman PC, Price LB, Cress ME, and Conley KE**. Large energetic adaptations of elderly muscle to resistance and endurance training. *Journal of Applied Physiology* 90: 1663-1670, 2001.
24. **Kusy K, and Zielinski J**. Sprinters versus long-distance runners: how to grow old healthy. *Exercise and sport sciences reviews* 43: 57-64, 2015.
25. **Malatesta D, Simar D, Saad HB, Préfaut C, and Caillaud C**. Effect of an overground walking training on gait performance in healthy 65-to 80-year-olds. *Experimental gerontology* 45: 427-434, 2010.
26. **Mangione KK, McCully K, Gloviak A, Lefebvre I, Hofmann M, and Craik R**. The effects of high-intensity and low-intensity cycle ergometry in older adults with knee osteoarthritis. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* 54: M184-M190, 1999.
27. **Martin PE, Rothstein DE, and Larish DD**. Effects of age and physical activity status on the speed-aerobic demand relationship of walking. *J Appl Physiol (1985)* 73: 200-206, 1992.
28. **Mendell LM**. The size principle: a rule describing the recruitment of motoneurons. *Journal of Neurophysiology* 93: 3024-3026, 2005.
29. **Mian OS, Thom JM, Ardigo LP, Morse CI, Narici MV, and Minetti AE**. Effect of a 12-month physical conditioning programme on the metabolic cost of walking in healthy older adults. *Eur J Appl Physiol* 100: 499-505, 2007.
30. **Mian OS, Thom JM, Ardigo LP, Narici MV, and Minetti AE**. Metabolic cost, mechanical work, and efficiency during walking in young and older men. *Acta Physiol (Oxf)* 186: 127-139, 2006.

31. **Mogensen M, Bagger M, Pedersen PK, Fernström M, and Sahlin K**. Cycling efficiency in humans is related to low UCP3 content and to type I fibres but not to mitochondrial efficiency. *The Journal of physiology* 571: 669-681, 2006.
32. **Musolf SA, and Ortega JD**. THE EFFECTS OF AGING ON THE METABOLIC COST OF SUPPORTING BODY WEIGHT DURING WALKING.
33. **Ortega JD, Beck ON, Roby JM, Turney AL, and Kram R**. Running for Exercise Mitigates Age-Related Deterioration of Walking Economy. *PLoS ONE* 9: 7p, 2014.
34. **Ortega JD, and Farley CT**. Effects of aging on mechanical efficiency and muscle activation during level and uphill walking. *Journal of Electromyography and Kinesiology* 25: 193-198, 2015.
35. **Ortega JD, and Farley CT**. Effects of aging on mechanical efficiency and muscle activation during level and uphill walking. *Journal of Electromyography & Kinesiology* 25: 6p, 2015.
36. **Ortega JD, and Farley CT**. Individual limb work does not explain the greater metabolic cost of walking in elderly adults. *J Appl Physiol (1985)* 102: 2266-2273, 2007.
37. **Ortega JD, and Farley CT**. Minimizing center of mass vertical movement increases metabolic cost in walking. *J Appl Physiol (1985)* 99: 2099-2107, 2005.
38. **Ortega JD, Fehlman LA, and Farley CT**. Effects of aging and arm swing on the metabolic cost of stability in human walking. *J Biomech* 41: 3303-3308, 2008.
39. **Peat G, McCarney R, and Croft P**. Knee pain and osteoarthritis in older adults: a review of community burden and current use of primary health care. *Annals of the rheumatic diseases* 60: 91-97, 2001.
40. **Peiffer JJ, Abbiss CR, Chapman D, Laursen PB, and Parker DL**. Physiological characteristics of masters-level cyclists. *The Journal of Strength & Conditioning Research* 22: 1434-1440, 2008.
41. **Peterson DS, and Martin PE**. Effects of age and walking speed on coactivation and cost of walking in healthy adults. *Gait Posture* 31: 355-359, 2010.
42. **Sacchetti M, Lenti M, Di Palumbo AS, and De Vito G**. Different effect of cadence on cycling efficiency between young and older cyclists. *Med Sci Sports Exerc* 42: 2128-2133, 2010.
43. **Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M, Brach J, Chandler J, Cawthon P, Connor EB, Nevitt M, Visser M, Kritchevsky S, Badinelli S, Harris T, Newman AB, Cauley J, Ferrucci L, and Guralnik J**. Gait speed and survival in older adults. *JAMA* 305: 50-58, 2011.
44. **Thomas EE, De Vito G, and Macaluso A**. Speed training with body weight unloading improves walking energy cost and maximal speed in 75- to 85-year-old healthy women. *J Appl Physiol (1985)* 103: 1598-1603, 2007.
45. **Van de Putte M, Hagemeister N, St-Onge N, Parent G, and De Guise J**. Habituation to treadmill walking. *Bio-medical materials and engineering* 16: 43-52, 2006.
46. **Venturelli M, and Richardson RS**. Point: skeletal muscle mechanical efficiency does increase with age. *J Appl Physiol (1985)* 114: 1108-1109, 2013.

47. **Wall J, and Charteris J**. A kinematic study of long-term habituation to treadmill walking. *Ergonomics* 24: 531-542, 1981.

APPENDICES

Tables

Table 1. Subject characteristics

	Young Adults Mean ± SD	Older Walkers Mean ± SD	Older Bicyclists Mean ± SD
Age (years)	23.6 ± 2.0	70.8 ± 4.9	68.4 ± 2 .9
Height (m)	1.69 ± 0.09	1.62 ± 0.09	1.73 ± 0.07
Leg length (m)	0.89 ± 0.06	0.88 ± 0.05	0.93 ± 0.05
Body mass (kg)	71.4 ± 15.9	69.1± 11.4	74.0 ± 9.0

Table 2. Resting and net metabolic cost at each walking speed

	Young Adults Mean ± SEM	Older Walkers Mean ± SEM	Older Bicyclists Mean ± SEM
Resting metabolic cost (Watts/kg)	1.25 ± 0.08	1.21 ± 0.04	1.28 ± 0.04
Net metabolic cost (Watts/kg)			
0.75 m/s	1.65 ± 0.08	2.15 ± 0.13	1.97 ± 0.09
1.25 m/s	2.61 ± 0.10	3.23 ± 0.15	2.69 ± 0.11
1.60 m/s	3.82 ± 0.20	4.40 ± 0.14	3.79 ± 0.17

1.75 m/s	4.78 ± 0.20	5.39 ± 0.20	4.52 ± 0.17

Table 3. Stride length at each walking speed

	Young Adults Mean ± SEM	**Older Walkers Mean ± SEM**	**Older Bicyclists Mean ± SEM**
Stride length			
0.75 m/s	1.02 ± 0.01	0.99 ± 0.03	0.98 ± 0.02
1.25 m/s	1.38 ± 0.01	1.32 ± 0.02	1.41 ± 0.04
1.60 m/s	1.60 ± 0.02	1.52 ± 0.03	1.63 ± 0.02
1.75 m/s	1.66 ± 0.02	1.59 ± 0.03	1.71 ± 0.02

Figures

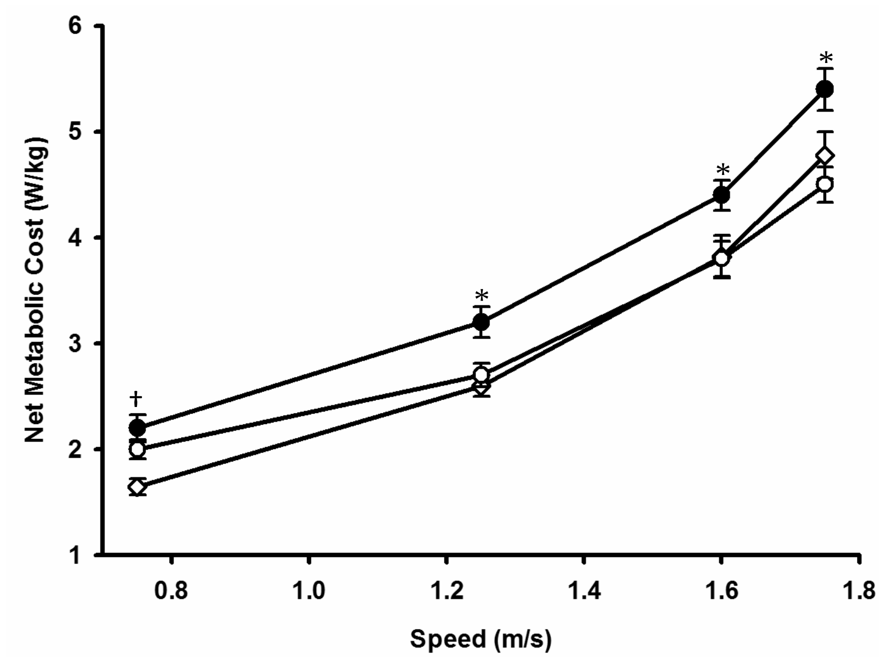

Figure 1. Mean (SE) net metabolic cost as a function of walking speed in young adults (◇), older walkers (●) and older bicyclists (○). Asterisks (*) represents significant differences between older bicyclists and older walkers. Cross (†) represents significant difference between older bicyclists and young adults. There was a significant difference at all speeds, between young adults and older walkers. (p<.05).

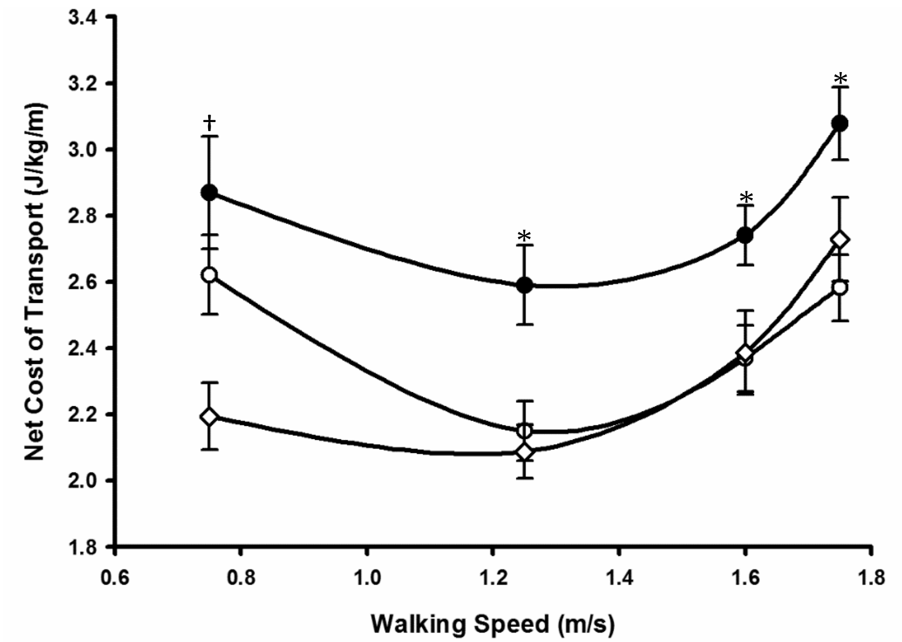

Figure 2 Mean (SE) net metabolic cost of transport as a function of walking speed in young adults (◇), older walkers (●) and older bicyclists (○). (Metabolic energy per kilogram of body weight to travel a given distance.) Asterisks (*) represents significant differences between older bicyclists and older walkers. Cross (†) represents significant difference between older bicyclists and young adults. There was a significant difference at all speeds, between young adults and older walkers. (p<.05).