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ORIGINAL ARTICLE

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Effect of a 12-month physical conditioning programme on the metabolic cost of walking in healthy older adults

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Abstract The metabolic cost of walking (C_W) is increased in healthy older adults. Previously, this has been suggested to be associated with age-related decline in physiological/functional factors such as stability and muscle size and strength. Physical training can improve such factors as well as aspects of gait performance in older adults. The aim of this investigation was to determine if it also has a beneficial impact on (lowers) C_W. Thirty-eight community dwelling older adults (aged 70–82 years) assigned to a training group (TRA, $n = 25$) or a control group (CON, $n = 13$) participated in a 12-month intervention. TRA followed a multi-component physical conditioning programme involving supervised resistance, aerobic, and balance exercises twice per week. They also undertook home based exercises once per week. CON carried on with their normal daily activities. C_W and indicators of functional capacity (knee extensor isometric strength, single leg balance time, sit and reach, stand and reach, and 6 min walk distance) were assessed prior to and following the intervention. Significant improvements in knee extensor isometric strength (+21%), single leg balance time (+30%), and 6 min walk distance (+6%) were observed in TRA ($P < 0.05$) but not in CON. However, no change in C_W was observed. In conclusion, this investigation has shown that a multi-component physical conditioning programme had a beneficial impact on functional capacity but did not lower C_W in healthy community dwelling older adults.

Keywords Economy · Mobility · Gait · Elderly · Ageing

Introduction

The metabolic energy used to walk a given distance, termed cost of walking (C_W), is elevated in healthy older adults even when free from gait impairment (Larish et al. 1988; Waters et al. 1988; Martin et al. 1992; McCann and Adams 2002; Malatesta et al. 2003). In itself, the age-related decline in maximum aerobic power (reviewed in Hawkins and Wiswell 2003) means that, at a given walking speed, relative exercise intensity is elevated in older adults. The increase in C_W exacerbates this further. As a result, older adults may walk at a slower, more tolerable pace, and many may be discouraged from maintaining activity levels due to the effort involved. Thus in addition to reduced muscle strength, cardio respiratory fitness, and dynamic stability, the increase in C_W should be considered as a contributory factor to mobility impairment. Previous authors have suggested that reductions in physical capacities in old age, such as loss of muscle mass/strength and decline in stability, may contribute to the increase in C_W (Martin et al. 1992; Malatesta et al. 2003). Hence, it could be hypothesised that improvement in physical capacities following physical conditioning will transfer to a reduction in C_W.

Physical training utilising resistance, aerobic, and mixed resistance and balance training has been shown to benefit aspects of gait performance in older adults with improvements in walking velocity (Cunningham et al. 1986; Judge et al. 1993; Sipila et al. 1996; Schlicht et al. 2001), step length (Judge et al. 1993), obstacle negotiation (Lamoureux et al. 2003), walking endurance (Ades et al. 1996) and gait stability (Krebs et al. 1998; Hausdorff et al. 2001a) reported in previous studies. However, the impact of physical training on C_W in older adults has

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not been investigated. Physical training has been shown to partially reverse the elevated C_W in cardiac patients (Beneke and Meyer 1997) and a reduction in the cost of running is sometimes observed after training regimes in novice and recreational runners (reviewed in Saunders et al. 2004). Thus, the purpose of this investigation is to determine if a structured physical-conditioning programme designed to improve multiple physical capacities results in a reduction in C_W in healthy older adults.

Methods

Participants

Participants in this investigation were a sub-sample of a larger group who had volunteered for a study at our institution investigating the impact of a 12-month physical conditioning intervention on numerous aspects of muscle weakness and locomotor function in old age (European Commission framework V project: Better Ageing). Exclusion criteria included chronic neurological, musculoskeletal, metabolic, endocrine, cardiovascular, and respiratory disorders. All participants admitted were community dwelling, independently mobile, and considered themselves to be in good general health. All methods and procedures had been approved by the institutional ethics committee and participants gave informed consent prior to participation. Participants had been randomly assigned to the training group (TRA) or non-training control group (CON) for the larger study. Twenty-nine individuals from TRA and 18 individuals from CON participated in the baseline measurements required for the current analysis. Two participants in TRA and four in CON withdrew during the intervention. Data for two participants in TRA and one participant in CON was lost due to technical difficulties. Thus, data for the current analysis was available from 25 and 13 participants in TRA and CON, respectively. Physical characteristics of the groups are shown in Table 1. All measurements were made pre- and post intervention, post measurements being completed within 2 weeks after the end of the intervention period. To confirm that the participants of this study had an elevated C_W (and therefore potential for improvement) baseline measurements of C_W in the older adults were compared to a sample of 20 young adults of similar physical characteristics (Table 1) recruited from the university community.

Interventions

Participants in TRA underwent a 12-month tailored physical conditioning program for older individuals. The programme was intended to incorporate exercises to target the causes of muscle weakness, poor balance, and poor mobility. Per week, participants attended two supervised sessions (held at a university gym and led by a certified fitness instructor) and completed one home based session. All sessions lasted 1 h.

Each supervised session commenced with 10 min of warm up activities. Following this was a 12-min, instructor led, group aerobic workout involving low impact walking and stepping with changes of direction to challenge balance maintenance. This included for example, forward, backward, side and diagonal heel and toe taps; forward, backward, and sideway walks; knee raises and lunges. Upper body movements such as arm raises, crosses, and curls were also incorporated into these movements. This was set to music paced at 118–124 beats per minute. Following this was 25 min of resistance training. Two sets (increasing to three after 6 months) of 8–10 repetition maximums were performed on each of the following machines: leg press, leg extension, calf raise, chest press, and seated row. Training load was reviewed and adjusted at the start of each month. In addition, resistance bands were used to strengthen the muscle groups not targeted specifically by the resistance machines. The final 10 min was a cool down period, involving stretching of the major muscle groups and Tai-chi exercises.

For the home based session, participants followed a guide book provided by the investigators. This session involved a brisk walk (20–40 min) followed by strengthening of major muscle groups with resistance bands and stretching exercises (20 min). Adherence was good with participants attending, on average, 91% of supervised sessions and reporting completion of 92% of home based sessions. Participants in CON carried on

Table 1 Mean ± SD physical characteristics of the training group (TRA), the control group (CON), the older group as a whole (TRA and CON) and a group of young adults used for comparison of cost of walking

	TRA	CON	Older adults	Young adults
Participants (*n*)	25	13	38	20
Males (%)	52	46	50	50
Age (years)	73.4 ± 3.4	73.2 ± 3.7	73.3 ± 3.5	26.7 ± 3.2*
Height (cm)	165.2 ± 7.7	163.7 ± 7.3	164.7 ± 7.5	168.8 ± 8.0
Leg length (cm)	86.5 ± 4.6	86.0 ± 4.7	86.3 ± 4.6	87.4 ± 3.4
Mass (kg)	73.2 ± 14.5	67.0 ± 7.1	71.1 ± 12.7	69.1 ± 11.0
Standing VO_2 (ml O_2 (kg min)$^{-1}$)	4.1 ± 0.8	4.2 ± 0.7	4.1 ± 0.8	4.0 ± 0.6

No statistically significant differences between TRA and CON

*Significant difference between young and older adults ($P < 0.01$)

with their normal daily activities and were asked not to take on new vigorous activities.

Cost of walking

Measurements were made whilst participants walked on a motor-driven treadmill (Woodway Ergo ELG 70, Weil am Rhein, Germany) at four different speeds (0.83, 1.11, 1.39, 1.67 m/s). Participants were thoroughly familiarised with treadmill walking at all the speeds on a previous visit. Participants walked with flat, soft-soled/sport shoes and prior to measurements they had abstained from food for 2 h.

Rate of oxygen consumption ($\dot{\mathrm{V}}\mathrm{O}_2$) and heart rate were recorded on a breath by breath basis using a portable automated analyser worn across the torso (Cosmed K4b^2, Rome, Italy) and viewed in real-time on a nearby computer. At each speed, after real-time plots of $\dot{V}O_2$, heart rate, and respiratory exchange ratio (RER) indicated that metabolic steady state had been achieved data was collected for two further minutes for averaging (typically, participants were required to walk for a total of 5–6 min at each speed). Standing $\dot{V}O_2$ was then subtracted from gross $\dot{V}O_2$ to obtain net $\dot{V}O_2$. C_W was expressed as the oxygen consumed to move 1 kg of body mass 1 m (ml (kg m)$^{-1}$), and was obtained by dividing net $\dot{V}O_2$ (ml (kg min)$^{-1}$) by speed (m min^{-1}). This is an appropriate measure of C_W since RER was always below 1.0 confirming that aerobic metabolism was the main metabolic pathway. Four TRA and three CON were unable or unwilling to walk for long enough to attain metabolic steady state at 1.67 m s^{-1}. Thus C_W data at 1.67 m s^{-1} refers to 21 TRA and 10 CON.

Functional assessment

Measurements of maximum voluntary isometric contraction torque of the knee extensors (KE$_{\mathrm{MVC}}$), single leg balance time, sit-and-reach score, and 6 min walk distance are reported so that changes in C_W can be interpreted in light of changes in traditional outcome measures in the participants of this analysis. Right leg KE$_{\mathrm{MVC}}$ measurements were made on a Cybex dynamometer. Participants sat upright in the dynamometer chair with back fully supported and straps used to restrict movement to knee extension. The knee flexion/extension axis was lined up with the axis of rotation of the dynamometer arm and the knee joint angle was set at 70°. After warm up contractions, two maximum effort contractions were made and the greatest torque obtained was used to indicate KE$_{\mathrm{MVC}}$. Single leg balance time (length of time that participants could maintain balance whilst standing on their right leg with arms held by the side up to a maximum of 30 s) was recorded under eyes open (EO) and eyes closed (EC) conditions. The sit-and-reach test (Lemmink et al. 2003), conducted using a sit-and-reach box, was performed with both bare feet placed firmly against the box and the legs extended. Participants reached slowly forward along the measuring board. The distance from the toe (zero) line was measured (positive distance if participants reached beyond the toe line, and negative distance if participants could not reach the toe line). Three trials were performed and the best score was used. The 6 min walk test (6-MWT) (Bean et al. 2002) was conducted in a gymnasium by asking participants to walk around a rectangular circuit (45 m perimeter) as many times as possible in 6 min.

Statistics

Data for males and females were pooled as there is no gender difference in C_W (Waters et al. 1988; Thom et al. 2003). Differences between groups at baseline were assessed using Student's *t* tests for physical and functional characteristics, and group × speed ANOVA for C_W. The effect of intervention was assessed using group × time ANOVA for physical and functional characteristics and group × time × speed ANOVA for C_W. As speed is well known to influence C_W (Margaria 1976), main effects of speed will not be reported. *t* tests were used to make appropriate pairwise comparisons only when ANOVA revealed significant interaction effects. Relationships between variables were investigated using Pearson's product moment correlation coefficient. Statistical significance was accepted when $P < 0.05$.

Table 2 Mean ± SD functional performance pre and post intervention in the training group (TRA) and control group (CON)

	TRA		CON		*P* value (ANOVA) group × time
	Pre	Post	Pre	Post	
KE$_{\mathrm{MVC}}$ (Nm kg^{-1})	2.02 ± 0.51	2.45 ± 0.63**	2.12 ± 0.42	2.20 ± 0.39	< 0.01*
Single leg balance EO (s)	14.0 ± 9.5	18.2 ± 11.0**	15.1 ± 9.5	11.0 ± 10.3	0.025*
Single leg balance EC (s)	3.5 ± 1.4	4.4 ± 2.4	3.3 ± 1.3	2.6 ± 0.8	0.031*
Sit-and-reach (cm)	4.9 ± 8.0	4.1 ± 7.9	5.0 ± 6.4	5.9 ± 6.1	0.197
6 min walk distance (m)	587 ± 90	624 ± 88**	590 ± 65	589 ± 63	< 0.01*

No baseline differences between groups ($P > 0.05$)
ANOVA interaction effects: *$P < 0.05$. Post hoc comparisons: different from pre intervention, **$P < 0.05$

Results

Functional performance

Functional performance data are shown in Table 2. No significant differences between TRA and CON were apparent at baseline. Training led to improvement in strength with a significant 21% increase in average KE_{MVC} ($P < 0.01$) and no significant change in CON. Exercise training had a beneficial impact on static balance with average single leg balance time (EO) increased by 30% in TRA ($P = 0.046$) with a non-significant reduction in CON. A similar group × time interaction was seen for single leg balance time (EC), although the 26% increase in average single leg balance time (EC) in TRA narrowly failed to achieve statistical significance in post hoc analysis ($P = 0.06$). Average 6-MWT distance increased by 6% in TRA ($P < 0.01$) with no change in CON. There were no detectable changes in sit-and-reach scores in either group. Overall, the data indicates a clear improvement in functional capacity in TRA relative to CON. An additional point of note is that there was a positive correlation between KE_{MVC} and 6-MWT distance at baseline ($r = 0.45$, $P < 0.01$), and in TRA increase in KE_{MVC} was positively correlated with increase in 6-MWT distance ($r = 0.53$, $P < 0.01$).

Cost of walking

At baseline, C_W was significantly higher in the older adults than in the younger comparison group ($P < 0.01$) by an average across speeds of 25% (Fig. 1). Expressed as gross (i.e., including resting metabolism) instead of net metabolic cost the average percentage elevation was 18%. At baseline, there was no significant difference between TRA and CON in C_W. The intervention had no impact on C_W (Fig. 2). Since standing $\dot{V}O_2$ is used in the calculation of C_W, it should also be noted that the intervention had no impact on standing $\dot{V}O_2$ (Pre data shown in Table 1. Post TRA = 4.2 ± 0.7 ml (kg min)$^{-1}$, Post CON = 4.4 ± 0.8 ml (kg min)$^{-1}$, $F_{gp\times time} = 0.35$). No relationships between C_W and functional performance measures or change in C_W and change in functional performance were detected.

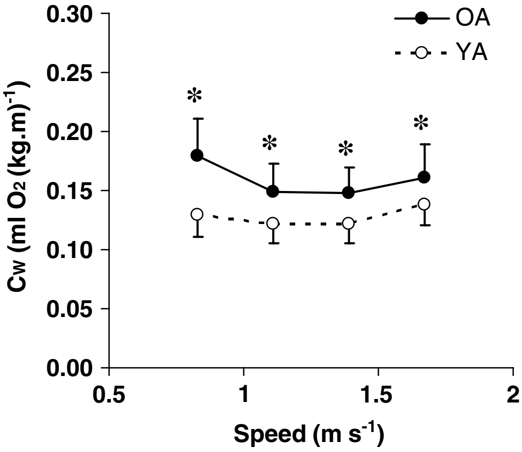

Fig. 1 Mean and SD net cost of walking (C_W) at baseline in older adults (*OA*; *filled circles* and *solid line*) and young adults (*YA*; *open circles* and *dashed line*). Significant main effect of age (F_{age}, $P < 0.01$). Interaction effect ($F_{age\times speed}$, $P < 0.01$) due to a larger relative increase in OA at the slowest speed compared to the higher speeds. Post hoc comparison: *Difference between OA and YA at given speed, $P < 0.01$

Discussion

Comparison of baseline 6-MWT distance with previous literature (Bean et al. 2002; Steffen et al. 2002; Seynnes et al. 2004) is consistent with the description of the older participants of the current study as healthy and without functional limitation. At baseline, C_W of the older participants in this study was elevated relative to young adults in line with previous observations (Larish et al. 1988; Martin et al. 1992; McCann and Adams 2002; Malatesta et al. 2003), and confirming that there was potential for improvement. A 1-year physical conditioning programme resulted in significant improvements in functional capacity but this was not accompanied by reductions in C_W. These findings agree with cross-sectional data indicating similar elevations in C_W in both sedentary and active healthy older adults relative to young adults (Martin et al. 1992).

A 27% reduction in C_W has been shown following aerobic training on a cycle ergometer and treadmill in patients with chronic heart failure (Beneke and Meyer 1997). Aside from the differences in participant groups, Beneke and Meyer's study (1997) was different to ours in other notable aspects. Unlike our study, they employed a training mode specific to the outcome measure. Also, they measured C_W at freely-chosen speeds. Whilst healthy young adults freely select speeds that are, metabolically, most economical (Ralston 1958), the participants in Beneke and Meyer (1997) had very low pre-training walking speeds (0.68 m s^{-1}) which after training increased to 1.16 (m s^{-1}). Therefore, in addition to any improvement attributable to a more economical walking pattern a substantial portion of the improvement in walking economy was accounted for by a shift away from an uneconomical region of the C_W–speed relationship toward the optimum region. In the current study, only a more economical walking pattern could have contributed to a change in C_W as speed was experimentally controlled. The typical reduction in habitual walking speed from ~1.3–1.5 m s^{-1} in young adults to ~1.1–1.3 m s^{-1} in healthy community dwelling septuagenarians (Himann et al. 1988; Oberg et al. 1993; Samson et al. 2001) is not large enough to cause a shift away from the relatively large plateau region of the C_W–speed relationship as confirmed in a number of studies (Larish et al. 1988; Martin et al. 1992; Thom et al. 2003), indicating that the increase in C_W in this group is due mainly to altered

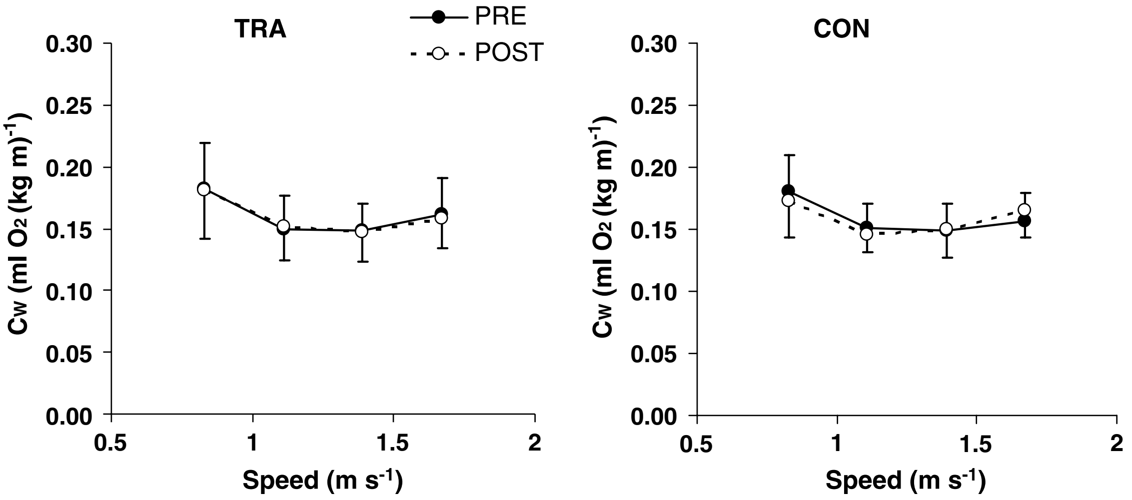

Fig. 2 Mean and SD net cost of walking (C_W) pre (*filled circles* and *solid lines*) and post (*open circles* and *dashed lines*) intervention in the training group (*TRA*) and control group (*CON*). No baseline differences between groups (F_{group}, $P = 0.99$; $F_{\mathrm{group \times speed}}$, $P = 0.86$). No intervention effect in either group ($F_{\mathrm{group \times time}}$, $P = 0.61$; $F_{\mathrm{group \times speed \times time}}$, $P = 0.43$)

walking mechanics or some other underlying physiological cause. Thus improvements in habitual gait speed after physical training (~0.1 m s^{-1}) seen in previous studies (Cunningham et al. 1986; Judge et al. 1993) would have little direct impact on C_W in healthy septuagenarians. To improve walking economy in this group, modification of factors that impact on C_W independently of speed is required. In this regard, implications of the current investigation are now discussed.

It has been suggested (Martin et al. 1992; Malatesta et al. 2003) that a reduction in muscle size and specific force in old age (e.g., Frontera et al. 2000) would require recruitment of a greater number of motor units, increasing the contribution of fast twitch fibres to walk at a given speed, an effect which may be detrimental to economy (cf, Krustrup et al. 2004). It could be noted that such a deduction might be less straightforward if there are shifts in fibre type/myosin heavy chain isoform composition in old age as demonstrated by some authors (reviewed in Andersen 2003). In addition to recruitment of additional motor units, reduction of muscle size may also result in increased level of activation of already recruited muscle fibres to achieve a given task which might be detrimental to muscle efficiency (Buschman et al. 1996) and hence locomotor economy. A link between reduced muscle size and increased C_W in old age was recently supported by an inverse relationship between C_W and knee extensor strength (Malatesta et al. 2003). In contrast we found no relationship at baseline between KE_{MVC} and C_W (Fig. 3). The participants in the current study were aged 70–82 whilst Malatesta et al. (2003) included participants aged 20–86 in their analysis. It is possible, therefore, that the heterogeneity in our sample may not have been large enough to detect a relationship, alternatively the possibility that C_W and strength (muscle size) are simply related to age rather than independently to each other cannot be excluded from the previous observations (Malatesta et al. 2003). More robust evidence would be provided if an intervention that increased muscle size and strength led to a reduction in C_W. We observed that training induced significant gains in knee extensor strength in this study. In addition, in a sub-group of the participants of the present study we have observed enhancements in isometric plantar flexor MVC (+20%), triceps surae muscle volume (+12%), and MVC normalised to volume (+8%) following the training program (Morse et al. 2005). However, there was no concomitant change in C_W or relationship between change in C_W and change in KE_{MVC} as a result of the intervention. These findings do not support the suggestion that the decline in muscle size and strength in healthy older adults is a major determinant of the elevated C_W.

Gait instability offers an intuitively appealing hypothesis to account for the higher C_W in older adults (Malatesta et al. 2003). Gait instability would require extra activation of postural and antagonist muscle groups to maintain dynamic balance. The training program in the current study involved components that were designed to challenge balance maintenance and static balance improved after training. At baseline we observed no relationship between C_W and static balance, nor did we observe a relationship between change in balance and change in C_W. There is evidence of an association between static balance and stride variability (Hausdorff et al. 2001a, b), a common measure of gait stability. However, an improvement in gait stability cannot be inferred from an improvement in static balance. The measurement of stability during walking would have been required to properly address the issue of its role in C_W. Malatesta et al. (2003) did not observe a relationship between the elevated C_W and elevated stride variability in their study, suggesting sample size may have been a factor in the failure to detect a relationship. This area remains equivocal and warrants further investigation.

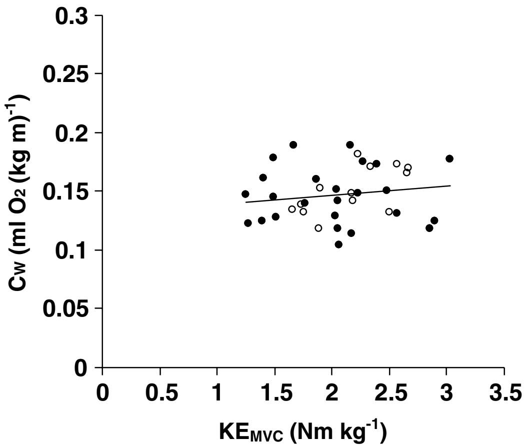

Fig. 3 Knee extensor isometric maximum voluntary contraction torque (KE_{MVC}) plotted against net cost of walking (C_W). No relationship was present ($r = 0.15$, $P = 0.36$). Data shown are for C_W at 1.11 m s^{-1}. *Solid circles* denote training group (*TRA*) and *open circles* denote control group (*CON*)

It has been speculated that internal resistance to motion could result in either a modified gait pattern that is less economical or to an increased force requirement (and associated metabolic demand) to produce the same gait pattern (Martin and Morgan 1992). Therefore, the decline in flexibility in old age (Roach and Miles 1991; Grimston et al. 1993) is another potential contributor to the elevated C_W. We observed no relationship between an indicator of flexibility (sit-and-reach score) and C_W, consistent with reports of no relationship or an inverse relationship between muscle tightness and cost of locomotion in young adults (Saunders et al. 2004). As flexibility did not improve in TRA we cannot judge whether interventions that improve flexibility influence C_W in older adults.

The exercise intervention used in the current investigation was a generic training programme aimed at improving general physical capacity and functioning in older individuals, and hence was not designed specifically to target gait economy. Nevertheless, the type of training used (resistance, aerobic, and balance) has been shown to be beneficial to aspects of gait performance in older adults with improvements in walking velocity, endurance, stability, and obstacle negotiation having been observed in previous studies (Cunningham et al. 1986; Judge et al. 1993; Ades et al. 1996; Sipila et al. 1996; Krebs et al. 1998; Hausdorff et al. 2001a; Schlicht et al. 2001; Lamoureux et al. 2003). Furthermore, the multi-factorial nature of the intervention is advocated by relevant organizations (e.g., ACSM 1998) therefore our finding of lack of impact on C_W has wide implications. Whilst multi-factorial in nature, the resistance training component was dominant in the intervention. The aerobic component of the supervised sessions was relatively short and aerobic exercise intensity was not individualised. Stronger aerobic and dynamic balance components may be necessary to impact on C_W in older adults and this should be addressed in future studies.

Whilst C_W was not improved as a result of training, it should be reinforced that a common indicator of maximum walking capacity, 6-MWT distance, was improved. The increase in distance in the current study can be interpreted as increase in the maximum maintainable speed of walking from 1.63 to 1.73 m s^{-1}. Although the magnitude of increase is relatively small ($<10\%$), the benefit to quality of life of being capable of maintaining a fast speed when desired may be considerable. Larger improvements in 6-MWT distance following exercise training have been seen in institutionalised older adults with low functional mobility at baseline (Seynnes et al. 2004). The 6-MWT distance is strongly related to lower limb strength and power in older adults (Bean et al. 2002; Seynnes et al. 2004), therefore its improvement after resistance training was anticipated. In the current study positive correlations were observed between KE_{MVC} and 6-MWT distance at baseline, and change in 6-MWT distance and change in KE_{MVC} after training.

In conclusion, an exercise training programme that enhanced the physiological capacity of healthy community dwelling older individuals did not improve walking economy. This observation may not apply to older individuals with functional impairment in whom the role played by limitations in walking speed, muscle size and strength, and balance could be more pronounced.

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References

Ades PA, Ballor DL, Ashikaga T, Utton JL, Nair KS (1996) Weight training improves walking endurance in healthy elderly persons. Ann Intern Med 124:568–572

American College of Sports Medicine (1998) Position stand: exercise and physical activity for older adults. Med Sci Sports Exerc 30:992–1008

Andersen JL (2003) Muscle fibre type adaptation in the elderly human muscle. Scand J Med Sci Sports 13:40–47

Bean JF, Kiely DK, Leveille SG, Herman S, Huynh C, Fielding R, Frontera W (2002) The 6-minute walk test in mobility-limited elders: what is being measured? J Gerontol A Biol Sci Med Sci 57:M751–756

Beneke R, Meyer K (1997) Walking performance and economy in chronic heart failure patients pre and post exercise training. Eur J Appl Physiol Occup Physiol 75:246–251

Buschman HP, Elzinga G, Woledge RC (1996) The effects of the level of activation and shortening velocity on energy output in type 3 muscle fibres from *Xenopus laevis*. Pflugers Arch 433:153–159

Cunningham DA, Rechnitzer PA, Donner AP (1986) Exercise training and the speed of self-selected walking pace in men at retirement. Can J Aging 5:19–26

Frontera WR, Suh D, Krivickas LS, Hughes VA, Goldstein R, Roubenoff R (2000) Skeletal muscle fiber quality in older men and women. Am J Physiol Cell Physiol 279:C611–C618

Grimston SK, Nigg BM, Hanley DA, Engsberg JR (1993) Differences in ankle joint complex range of motion as a function of age. Foot Ankle 14:215–222

Hausdorff JM, Nelson ME, Kaliton D, Layne JE, Bernstein MJ, Nuernberger A, Fiatarone Singh MA (2001a) Etiology and modification of gait instability in older adults: a randomized controlled trial of exercise. J Appl Physiol 90:2117–2129

Hausdorff JM, Rios DA, Edelberg HK (2001b) Gait variability and fall risk in community-living older adults: a 1-year prospective study. Arch Phys Med Rehabil 82:1050–1056

Hawkins SA, Wiswell RA (2003) Rate and mechanism of maximal oxygen consumption decline with aging: implications for exercise training. Sports Med 33:877–888

Himann JE, Cunningham DA, Rechnitzer PA, Paterson DH (1988) Age-related changes in speed of walking. Med Sci Sports Exerc 20:161–166

Judge JO, Underwood M, Gennosa T (1993) Exercise to improve gait velocity in older persons. Arch Phys Med Rehabil 74:400–406

Krebs DE, Jette AM, Assmann SF (1998) Moderate exercise improves gait stability in disabled elders. Arch Phys Med Rehabil 79:1489–1495

Krustrup P, Soderlund K, Mohr M, Bangsbo J (2004) Slow-twitch fiber glycogen depletion elevates moderate-exercise fast-twitch fiber activity and O2 uptake. Med Sci Sports Exerc 36:973–982

Lamoureux EL, Murphy A, Sparrow A, Newton RU (2003) The effects of progressive resistance training on obstructed-gait tasks in community-living older adults. J Aging Phys Act 11: 98–110

Larish DD, Martin PE, Mungiole M (1988) Characteristic patterns of gait in the healthy old. Ann NY Acad Sci 515:18–32

Lemmink K, Kemper HCG, de Greef MHG, Rispens P, Stevens M (2003) The validity of the sit-and-reach test and the modified sit-and-reach test in middle-aged to older men and women. Res Q Exerc Sport 74:331–336

Malatesta D, Simar D, Dauvillier Y, Candau R, Borrani F, Prefaut C, Caillaud C (2003) Energy cost of walking and gait instability in healthy 65- and 80-year-olds. J Appl Physiol 95:2248–2256

Margaria R (1976) Biomechanics and energetics of muscular exercise. Oxford University Press, Oxford, UK

Martin PE, Morgan DW (1992) Biomechanical considerations for economical walking and running. Med Sci Sports Exerc 24:467–474

Martin PE, Rothstein DE, Larish DD (1992) Effects of age and physical activity status on the speed-aerobic demand relationship of walking. J Appl Physiol 73:200–206

McCann DJ, Adams WC (2002) A dimensional paradigm for identifying the size-independent cost of walking. Med Sci Sports Exerc 34:1009–1017

Morse CI, Thom JM, Mian OS, Muirhead A, Birch KM, Narici MV (2005) Muscle strength, volume and activation following 12-month resistance training in 70-year-old males. Eur J Appl Physiol 95:197–204

Oberg T, Karsznia A, Oberg K (1993) Basic gait parameters: reference data for normal subjects, 10–79 years of age. J Rehabil Res Dev 30:210–223

Ralston HJ (1958) Energy–speed relation and optimal speed during level walking. Int Z Angew Physiol 17:277–283

Roach KE, Miles TP (1991) Normal hip and knee active range of motion: the relationship to age. Phys Ther 71:656–665

Samson MM, Crowe A, de Vreede PL, Dessens JA, Duursma SA, Verhaar HJ (2001) Differences in gait parameters at a preferred walking speed in healthy subjects due to age, height and body weight. Aging (Milano) 13:16–21

Saunders PU, Pyne DP, Telford RD, Hawley JA (2004) Factors affecting running economy in trained distance runners. Sports Med 34:465–485

Schlicht J, Camaione DN, Owen SV (2001) Effect of intense strength training on standing balance, walking speed, and sit-to-stand performance in older adults. J Gerontol A Biol Sci Med Sci 56:M281–M286

Seynnes O, Fiatarone Singh MA, Hue O, Pras P, Legros P, Bernard PL (2004) Physiological and functional responses to low-moderate versus high-intensity progressive resistance training in frail elders. J Gerontol A Biol Sci Med Sci 59A:503–509

Sipila S, Multanen J, Kallinen M, Era P, Suominen H (1996) Effects of strength and endurance training on isometric muscle strength and walking speed in elderly women. Acta Physiol Scand 156:457–464

Steffen TM, Hacker TA, Mollinger LA (2002) Age- and gender-related test performance in community dwelling elderly people: six-minute walk test, berg balance scale, timed up and go test, and gait speeds. Phys Ther 82:128–137

Thom JM, Mian O, Ardigò LP, Muirhead A, Minetti AE, Narici MV (2003) Metabolic cost of walking at set and self-selected speeds in older males and females. Med Sci Sports Exerc 35(Suppl 1):S296

Waters RL, Lunsford BR, Perry J, Byrd R (1988) Energy speed relationship of walking—standard tables. J Orthop Res 6: 215–222