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Walking Economy and Preferred Speed in Old and Very Old Men

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ABSTRACT

LUNEAU, E., V. ROZAND, D. RIMAUD, C. FOSCHIA, and G. Y. MILLET. Walking Economy and Preferred Speed in Old and Very Old Men. *Med. Sci. Sports Exerc.*, Vol. 57, No. 2, pp. 400–412, 2025. **Purpose:** With aging, the decline in preferred walking speed (PWS), influenced by the increased energy cost of walking (CoW), is a key predictor of morbidity. However, the determinants associated with PWS and CoW remain poorly understood, especially after 80 yr old. The aim of the study was to characterize the amplitude and mechanisms of age-related decline in CoW and PWS in old (OM) and very old (VOM) men. **Methods:** Thirty-nine young men (YM; 22.1 ± 3.4 yr), 34 OM (71.7 ± 4.1 yr), and 23 VOM (85.8 ± 2.7 yr) performed aerobic, neuromuscular, and gait assessments. Net CoW was measured on a treadmill. Physical activity (PA) was evaluated by questionnaire and accelerometry. **Results:** Net CoW was 32% ($P < 0.001$), 19% ($P < 0.01$), and 26% ($P < 0.001$) higher in VOM compared with OM for $1.11 \text{ m}\cdot\text{s}^{-1}$, $1.67 \text{ m}\cdot\text{s}^{-1}$, and PWS. Net CoW was also 27% ($P < 0.001$), 26% ($P < 0.01$), and 29% ($P < 0.001$) higher in OM compared with YM at these speeds. Linear regression stratified by age showed that net CoW at PWS was associated with step frequency ($r = 0.79$; $P < 0.001$) for OM and with both coefficient of variation of stride mean time ($r = 0.48$; $P < 0.05$) and maximal strength of knee extensors ($r = -0.54$; $P < 0.05$) for VOM. The same analysis revealed that PWS was correlated with net CoW ($r = -0.56$; $P < 0.05$) and PA ($r = 0.47$; $P < 0.05$) in VOM. **Conclusions:** The progressive increase in net CoW with age was associated with gait and neuromuscular impairments, particularly after the age of 80 yr. This increase in net CoW was related to a decrease in PWS in VOM, suggesting an adaptation of PWS to compensate for the increase in energy demand. Maintaining a high level of PA may potentially delay the age-related decline in PWS despite an age-related increase in net CoW. **Key Words:** AGING, ENERGY COST OF WALKING, GAIT VARIABILITY, PREFERRED WALKING SPEED, MAXIMAL STRENGTH, $\dot{V}O_{2\text{MAX}}$

Walking is the preferred physical activity (PA) in older adults and a key factor in maintaining an optimal quality of life (1). Energy cost of walking (CoW), defined as the metabolic energy expended per unit of distance, progressively increases with aging at comparable speeds (2). An increase in CoW can lead to a decline in activities of daily living in older adults, which is associated with a loss of autonomy and an increased risk of morbidity and mortality (3). Data on CoW in very old adults (>80 yr) are limited despite this population presenting exacerbated alterations in neuromuscular function compared with old adults (4,5) and being at higher risk of loss of autonomy (6). In addition, most

previous research has examined CoW with mixed-gender groups (7–13). Although there is no gender difference in CoW in older adults (7,14), it has been shown that men and women have specific walking pattern characteristics. In addition, some authors highlighted sex differences in gait kinematics and spatio-temporal parameters in young (15) and older (16) adults. Therefore, we decided to not recruit both men and women in the present study. Because the studies on CoW in aging population generally involved more women than men (7–13), we decided to focus on men.

The mechanisms of the increase in CoW with aging are unclear (1). Alterations due to visual perturbations, characterized by shorter, wider, and more variable steps, were associated with a significant increase in net CoW and net metabolic power (17,18). Aging is associated with a greater gait variability (19), which was associated with greater net CoW (20), despite some conflicting results (9). Other neural mechanisms, such as increased activation of antagonist muscles, have been associated with deteriorated CoW (1,11). Whereas the greater activation may be beneficial for the stability of the joints involved in gait, the additional metabolic energy required due to age-related increases in both agonist and antagonist activity could further elevate CoW (11).

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Aging is also associated with changes in gait biomechanics with a distal-to-proximal shift in muscle workload with age, favoring a hip rather than ankle strategy in the elderly population. (1). With advancing age, the decline in force/power of the plantar flexor is compensated by an increase in hip extensor torque, which may contribute to the greater net CoW (13). However, in this study, only the hip extensor but not the plantar flexor torque was an independent predictor of net CoW. Again, a limited sample size and sex differences in gait kinematics (15,16) may have affected the results. For a constrained speed ($0.89 \text{ m}\cdot\text{s}^{-1}$), $\dot{V}\text{O}_2$ consumption was positively associated with maximal isometric strength of the knee extensors and negatively associated with range of motion of the plantar flexors (21). However, this study included only older women, none of whom were over 80 yr of age. Other hypotheses have been proposed to explain the age-related alteration in CoW. For instance, a higher first ventilatory threshold (VT1) and a lower maximal strength in older adults could lead to a greater recruitment of less energetically efficient type II muscle fibers for a given walking speed (22). However, data on these parameters are scarce, and the results are inconclusive. In addition, the efficiency of contraction in the knee extensors (23) and in the plantar flexors (24) was altered in older compared with young adults, which could potentially affect CoW. Many biomechanical and neuromuscular factors can influence CoW, but age-related confounders could play a role in the interpretation of the results (2). For example, one study (9) found a significant correlation between maximal voluntary isometric contraction (MVC) torque of the knee extensors (KE) and gross CoW at $1.33 \text{ m}\cdot\text{s}^{-1}$ when pooling three different age groups (young: 20–29 yr, old: 60–69 yr, and very old: 77–86 yr). Because CoW increases and MVC decreases with age, the correlation between these two parameters may have been influenced by the effects of age in this study. In addition, the sample size was relatively small, and a majority of older participants in this study were women (14 out of 20). Therefore, an integrative approach including gait variability, maximal strength of lower limb muscles, and VT1 in old and very old men may help to better understand the biomechanical, neuromuscular, and energetic factors associated with the deterioration of CoW with aging.

In addition to the age-related decline in CoW, preferred walking speed (PWS) decreases with age by approximately 1% per year from the age of 60 (25), with an acceleration from the seventh decade (26). Factors contributing to changes in PWS in the elderly population are not fully understood, but may include impairments in lower limb strength/power (27,28), aerobic fitness (29), and balance and gross CoW (30,31). These alterations are modulated by both intrinsic (genetic) and extrinsic (lifestyle, level of PA) factors so that physical capacities would be more relevant than age in analyzing PWS. Indeed, maximal O_2 uptake ($\dot{V}\text{O}_{2\text{max}}$) (32) and calf strength (33) were better correlated with PWS than age. Several studies have suggested that age-related increase in gross CoW could explain the decline in PWS (30,31,34–36). Another investigation (29) found that PWS was highly correlated with aerobic parameters, such as $\dot{V}\text{O}_{2\text{max}}$, VT1, and $\dot{V}\text{O}_2$ as a percentage of VT1,

suggesting that the main contributor to PWS change is the aerobic level. As for CoW, the mechanisms explaining the age-related decrease in PWS remain unclear.

The first aim of the present study was therefore to describe the age-related evolution of CoW and PWS, especially after the age of 80. The secondary aim was to identify parameters associated with net CoW and PWS in young, old, and very old men using an integrative approach combining gait parameters, and neuromuscular and cardiorespiratory measurements. Because net CoW measurement was part of a broader study of the effects of aging on physical capacities, it was not possible to assess all parameters related to the increase in net CoW such as increased coactivation. We hypothesized that (i) age-related decline in plantar flexors strength and gait variability would be the main factors associated with net CoW in older adults, and (ii) aerobic capacity, i.e., VT1 and $\dot{V}\text{O}_{2\text{max}}$, and neuromuscular capacities, i.e., knee extensor and plantar flexor muscles strength, would be associated with PWS.

METHODS

Participants

Thirty-nine young men (YM; 22.1 ± 3.4 yr), 34 old men (OM; 71.7 ± 4.1 yr), and 23 very old men (VOM; 85.8 ± 2.7 yr) volunteered to participate in the study. All participants were healthy and free of clinically significant orthopedic, neurological, cardiovascular, or respiratory problems. VOM needed to score at least 20 at the Mini-Mental Stage Examination (28.6 ± 1.4). None of the participants were taking any medication that could alter gait parameters. All the procedures were approved by the ‘Comité de Protection des Personnes Nord-Ouest 1 (#21.00901.000003) and conducted in accordance with the Declaration of Helsinki. The study, sponsored by the University Hospital of Saint-Etienne, was submitted to ClinicalTrials.gov (identifier: NCT04516538). All the participants were clearly informed of the experimental procedures before giving their written consent.

Experimental Design

Participants visited the laboratory on three occasions separated by 7 to 10 days for a comprehensive evaluation of their physical capacities (Fig. 1). During the first visit, anthropometric measurements were collected before experimental procedures. Percentage body fat was determined with skinfold thickness measurement (37) at four different sites (i.e., biceps, triceps, subscapular, and supra-iliac). A maximal ramp test (38) was then performed on a recumbent cycle ergometer (RC6; Monark, Vansbro, Sweden) to assess maximal oxygen consumption ($\dot{V}\text{O}_{2\text{max}}$). At the end of the first visit, participants completed three questionnaires to assess fatigue (The Functional Assessment of Chronic Illness Therapy—Fatigue (FACIT-F)), quality of life (The Short Form 36 Health Survey (SF-36)), and PA (Global Physical Activity Questionnaire (GPAQ)). Finally, an accelerometer (wGT3X-BT; ActiGraph, Pensacola, FL) was

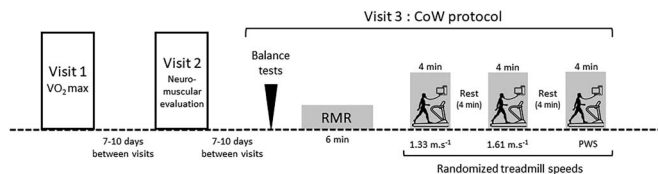


FIGURE 1—Experimental design of the study. During visits 1 and 2, the aerobic parameters, such as the maximal oxygen consumption and the first ventilatory threshold, and neuromuscular parameters, as the maximal isometric voluntary contraction for the right knee extensors, plantar flexors and dorsiflexors, were assessed. Visit 3 was the visit where the net cost of walking was measured at three different speeds on a treadmill. Net CoW, energy cost of walking; RMR, resting metabolic rate; $\dot{V}O_{2max}$, maximal oxygen uptake.

given to be worn for 7 consecutive days to objectively assess the level of PA.

During the second visit, the following neuromuscular tests were performed: (i) maximal voluntary isometric contraction of the KE (MVC KE), plantar flexors (MVC PF), and dorsiflexors (MVC DF); (ii) handgrip test; (iii) force–velocity profile on a cycle ergometer; and (iv) a fatigability test. Data from the FACIT-F, SF-36, force–velocity profile, and fatigue test are not presented in the present article. After 20 to 30 min of rest, the participants were familiarized to treadmill walking across experimental walking speeds during about 30 min.

The last visit started with functional assessments. Participants performed a 6-min walk test (6MWT) and a Timed-Up-and-Go (TUG) test. Balance was evaluated with two different tasks: tandem eyes open (TEO) and tandem eyes closed (TEC). Then, net CoW assessments were performed. Before net CoW assessment, resting metabolic rate (RMR) and overground PWS were determined. More familiarization was performed at experimental walking speeds. During this familiarization, the speed was increased slowly to ensure that older people could walk at $1.67 \text{ m}\cdot\text{s}^{-1}$. In total, a minimum of 30 min of familiarization was performed for each participant (8,9). All the procedures were performed on an instrumentalized treadmill (ADAL; HEF Techmachines, Andrézieux-Bouthéon, France). For net CoW assessment, participants walked for 4 min on the instrumentalized treadmill at three different speeds in a randomized order, i.e., $1.11 \text{ m}\cdot\text{s}^{-1}$, $1.67 \text{ m}\cdot\text{s}^{-1}$, and PWS. Each walk was separated by 4 min of rest on a chair. This duration was chosen to avoid any fatigue effects in older adults.

$\dot{V}O_{2max}$ and VT1

To assess $\dot{V}O_{2max}$, a maximal ramp test (38) was used on a recumbent cycle ergometer (RC6, Monark, Vansbro, Sweden) adapted for older adults. The load was increased gradually, and the slope of the ramp was adapted to the age and physical condition of the participants (from 5 to $20 \text{ W}\cdot\text{min}^{-1}$) so that the test lasted between 8 and 12 min. The cadence had to be maintained above 60 rpm. The test ended when participants were unable to maintain a cadence above 60 rpm for 10 s despite encouragement, or when participants voluntarily stopped exercising. Breath-by-breath ventilatory and gas exchange measurements ($\dot{V}O_2$ and $\dot{V}CO_2$) were assessed continuously using a metabolic card (Metamax 3B-R2; CORTEX, Leipzig, Germany) during all the protocol.

$\dot{V}O_{2max}$ was defined as the highest $\dot{V}O_2$ computed from a 20-s rolling average (38) and was considered achieved when

a plateau in $\dot{V}O_2$ was reached during 20 s; i.e., $\Delta\dot{V}O_2 < 50 \text{ mL}\cdot\text{min}^{-1}$ (39) was observed (40). If this criterion was not visible, two secondary criteria had to be met for the validation of a maximal test, i.e., $[\text{La}] > 9.0 \text{ mmol}\cdot\text{L}^{-1}$ for YM and $> 4.0 \text{ mmol}\cdot\text{L}^{-1}$ for OM and VOM, and $\text{RER} > 1.1$ for YM and > 1.0 for OM and VOM (41).

VT1 was determined by visual inspection of three different methods: 1) the first breakpoint of the ventilation versus workload curve (42), 2) the inflection point of $\dot{V}CO_2$ with respect to $\dot{V}O_2$ (43), and 3) the point at which the $\dot{V}O_2$ respiratory equivalent ($\dot{V}E/\dot{V}O_2$) increases while the $\dot{V}CO_2$ ventilatory equivalent ($\dot{V}E/\dot{V}CO_2$) remains stable (43). VT1 determination was performed by two experienced, independent investigators.

Strength Measurements

Knee extension. Assessment of maximal strength was performed in an isometric chair with a load cell fixed to the chair and attached to the participant's right leg, above the ankle malleolus, with a noncompliant strap (ARS dynamometry; SP2, Ltd., Ljubljana, Slovenia). A belt at pelvic level was used to avoid compensatory movements. Torque measurement was assessed on the right leg at 90° hip and knee extension. Before MVC was measured, participants performed a warm-up consisting of seven contractions of ~ 3 s each (two at 30%, two at 50%, and two at 70% of the estimated maximal force and one near maximal force). Then, participants performed two MVCs, separated by 1 min of rest. A third MVC was performed if the difference between the two MVCs was $> 5\%$. Participants were instructed to push "as hard as possible" and to hold the contraction for 4–5 s. Verbal encouragement was given during the MVC.

Plantar and dorsiflexion. Participants were comfortably seated on a custom-built ergometer with 90° of knee extension and 45° of plantar flexion. The right foot was strapped on an iron plate connected to the force sensor (Torque meter CS1060; FGP, Les Clayes sous Bois, France). After a standardized warm-up similar to the one performed for the knee extensors, the participants were asked to push as hard as possible during the MVC of the plantar flexion and to pull as hard as possible during the MVC of the dorsiflexion.

Force of the knee extension, plantar flexion, and dorsiflexion was assessed at a sampling rate of 2 kHz, transmitted without analogical or digital filter using a Power-Lab data acquisition system (16/30-ML880/P; ADInstruments, Bella Vista, Australia), and recorded on a personal computer through LabChart software

(v8; ADInstruments). Visual feedback was provided on a large screen positioned in front of participants.

Balance Measurements

The two tests described hereinafter were performed without shoes. Each task consisted of 30-s trials separated by 1 min of rest (44). Participants were asked to sit in a nearby chair during the rest period. Participants were given 3 min of rest between each task, i.e., TEO and TEC. These tasks are detailed hereinafter. Balance score of each task was defined as the sum of the time spent in the constrained position during the three 30-s trials for each task. If participants failed to complete the task, the time remaining in balance until stopping was recorded. If the participants were unable to get into the requested position, a score of 0 was assigned.

Tandem eyes opened. Participants were asked to stand upright in a comfortable position with the hands on the hips and to look straight ahead at a visual reference (2 m away). The feet had to be in line, one in front of the other, with visual cues symbolizing the center of the force platform (tandem position). The order of the supports was left free, but this order had to be maintained throughout the trials. If one of the feet left the starting position during the test or when the eyes of the participants were no longer looking at the cue in front of them, the task was stopped. Any compensatory movement was allowed as long as both feet were on the ground. The hands could leave the hips to restore balance, but they had to return to their place as soon as possible.

Tandem eyes closed. The same guidelines as above were followed for the eyes-closed task. Recording started when the participants closed their eyes. A visual check was made to ensure that participants did not open their eyes, even briefly. Opaque masks were not worn for safety reasons, especially for very old men.

The balance task was performed on force platform (Type 9287 CA; Kistler Instrumente AG, Winterthur, Switzerland), and the following posturographic parameters were assessed: path length, velocity, and 95% confidence ellipse area of the center of pressure.

Preferred Walking Speed

To determine PWS, participants walked indoor on a 25-m straight track (45) and PWS was assessed over the 5-m range between the 15th and 20th meters using photocell chronometers (Witty; Microgate, Bolzano, Italy). The last 5 m allowed us to ensure that the participant did not decelerate before the PWS was assessed. The following instructions were given to the participants: “Walk straight ahead at a walking speed where you feel comfortable.” Participants had to walk the full length of the track, and the distance (i.e., 5 m) was divided by the time measured between cells to obtain the speed. Two trials were performed, and the average was used as PWS. PWS was determined on the ground because treadmill assessment of PWS can lead to underestimation (45,46).

Resting Metabolic Rate

RMR was measured while the participants were seated on a chair for 6 min in a relaxed state. RMR was defined as the average of $\dot{V}O_2$ values over the last 2 min.

Energy CoW

Net CoW was measured during the 4-min walking trials at the three speeds, i.e., 1.11 m·s⁻¹, 1.67 m·s⁻¹, and PWS. Typically, the first 3 min of data was ignored as the person reached steady state, and the last minute was averaged to calculate the CoW. The trials started when the investigator was satisfied that the participants were walking naturally and comfortably.

The net CoW assessment began with a minimum of 2 min allowing each participant to adjust to the speed condition. Then, the 4-min trials started when the investigator was satisfied that the participants were walking naturally and comfortably. Net CoW was measured during the 4-min walking trials at the three speeds, i.e., 1.11 m·s⁻¹, 1.67 m·s⁻¹, and PWS. For all the participants, the first 3 min was ignored and the last minute was averaged to calculate net CoW. Breath-by-breath ventilatory and gas exchange measurements ($\dot{V}O_2$ and $\dot{V}CO_2$) were assessed continuously using a metabolic card (Metamax 3B-R2; CORTEX) during all the protocol. Inspired and expired flow rates were assessed using a turbine positioned on a face mask. Fractional concentrations of inspired and expired O₂ and CO₂ for each breath were measured by gas analyzers on the metabolic card. The turbine and the gas analyzers were calibrated before each test. In addition, heart rate was monitored using a thoracic belt (Polar H7; Polar, Kempele, Finland). Real-time assessment allowed us to visually ensure a steady state of heart rate, $\dot{V}O_2$ and $\dot{V}CO_2$, for at least 1 min. No participant failed to reach a steady state.

Respiratory exchange ratio (RER) was calculated from the data collected as $\dot{V}CO_2/\dot{V}O_2$. $\dot{V}O_2$ values from the last minute were averaged and normalized to body mass.

Net CoW (in J·kg⁻¹·m⁻¹) was calculated using the indirect calorimetry method:

$$\text{Net CoW} = ((\dot{V}O_2 - \text{RMR}) \times O_2 \text{ EEq}) \times \text{WS}^{-1}$$

where $\dot{V}O_2$ is the oxygen uptake (in mL O₂·kg⁻¹·min⁻¹), RMR is the resting metabolic rate (in mL O₂·kg⁻¹·min⁻¹), O₂ EEq is the O₂ energetic equivalent (in J·L·O₂⁻¹) calculated from RER (47), and WS is the walking speed (in m·min⁻¹).

Gait Parameters

During the walking trials, force plate (type KI 9067; Kistler, Winterthur, Switzerland) ground reaction force data were sampled at 200 Hz. Heel strike peak vertical ground reaction forces were assessed using the treadmill force plates. Stride time was defined as the interval between two consecutive heels strike peak vertical forces. Average stride time (STM) was used to calculate the stride time coefficient of variation (CV). Step frequency was defined as the number of peak vertical forces during the walking trial divided by the length of the trial.

Functional Tests

The 6MWT (48) consisted of covering the longest distance possible in 6 min on a corridor of 30 m. The participants then performed a TUG test (49), in which they were required to

stand up from a chair, walk a distance of three meters, turn around, return, and sit down on the chair as fast as possible.

PA Level

PA was estimated using two methods. The first one was by using the GPAQ that was developed and validated by the World Health Organization to systematically monitor global PA levels (50). The second method consisted of requiring participants to wear an accelerometer (wGT3X-BT; ActiGraph, Pensacola, FL) on the nondominant wrist for 7 consecutive days. Data were analyzed only if participants wore the accelerometer during 8 h per day for at least 6 d (5 out of 96 participants did not meet this criterion).

PA data during the wearing period were analyzed and quantified as steps per day using ActiLife software (v6.13.4; ActiGraph).

Differences among Very Old Men

Most of the VOM (13 out of 21) were unable to walk at $1.67 \text{ m}\cdot\text{s}^{-1}$. Therefore, VOM were divided into two groups: $\dot{V}O_{\text{fast}}$ who completed the walk at $1.67 \text{ m}\cdot\text{s}^{-1}$ and $\dot{V}O_{\text{slow}}$ who did not. Moreover, two VOM did not meet the $\dot{V}O_{2\text{max}}$ criteria and were excluded from the analysis. In addition, two participants (one OM and one VOM) had a respiratory exchange ratio greater than 1.0 during walking at $1.67 \text{ m}\cdot\text{s}^{-1}$ and were therefore also excluded from the analysis.

Statistics

Shapiro–Wilk and Levene tests were used to check normal distribution and equality of variance. As the conditions of normality and homogeneity of variances being fulfilled for each variable, a one-way ANOVA was used to determine differences in the participant's characteristics, resting $\dot{V}O_2$, aerobic and neuromuscular parameters, step frequency, CV of STM, and PWS among groups. A two-way repeated-measures ANOVA mixed design (speed–group) was performed to test the difference in net CoW between groups at the three different speeds. A Tukey *post-hoc* analysis was performed when a significant difference was found. Correlations between net CoW at different speeds (i.e., $1.11 \text{ m}\cdot\text{s}^{-1}$, $1.67 \text{ m}\cdot\text{s}^{-1}$, and PWS) and all variables assessed during the different tests were performed using the Pearson correlation coefficient (r) for each group (YM, OM, VOM) and all participants. The same analysis was performed between PWS and all variables for each group.

An unpaired *t*-test or a Mann–Whitney *U*-test (for nonparametric values, i.e., if the distribution was not normal or if the equality of variance was violated.) was used to compare neuromuscular, aerobic, and functional parameters between $\dot{V}O_{\text{fast}}$ and $\dot{V}O_{\text{slow}}$. $P < 0.05$ was considered as significant in all tests. The statistical analyses were performed with Jasp software (Jasp 0.18.3) except the Pearson correlation coefficients for each group that were calculated with MATLAB (R2022b).

RESULTS

Subjects' characteristics. There were no significant differences in body mass and body mass index (BMI) between the three groups ($P = 0.31$ and $P = 0.23$, respectively). Height was lower in OM and VOM than YM (both $P < 0.001$), and no significant difference was found between OM and VOM ($P = 0.21$; Table 1). Similar results were found for body fat with a significant difference between YM compared with OM and VOM (both $P < 0.001$). Again, no significant difference was observed between OM and VOM ($P = 0.44$). All neuromuscular variables declined with age. Compared with YM, a 36% and 58% lower MVC KE and a 15% and 36% lower MVC PF were observed for OM and VOM, respectively. Only VOM underwent a significantly lower MVC DF compared with YM and OM ($P = 0.02$).

Absolute and relative $\dot{V}O_{2\text{max}}$ as well as VT1 decreased with age. Absolute and relative $\dot{V}O_{2\text{max}}$ were 33% and 30% lower, respectively, for OM and 51% and 49% lower for VOM compared with YM (all $P < 0.001$). Absolute and relative VT1 decreased with age, i.e., -26% and -29% for OM and -41% and -42% for VOM compared with YM (all $P < 0.001$). VT1 expressed as a percentage of $\dot{V}O_{2\text{max}}$ differed only between YM and VOM ($P = 0.02$). Regarding postural parameters, the path lengths, i.e., total distance traveled by the center of pressure during the trial, of OM and VOM were 104% and 139% longer than the YM values, respectively (both $P < 0.001$). Consistent with previous results, the velocity of the center of pressure was 104% and 137% higher for OM and VOM, respectively, compared with YM (both $P < 0.001$).

TABLE 1. Subjects characteristics (mean \pm SD).

Variables	Young	Old	Very Old
<i>n</i>	39	34	21
Anthropometric			
Age, yr	22.1 \pm 3.4	71.6 \pm 4.2***	85.4 \pm 2.6***.†††
Height, cm	179.9 \pm 6.0	174.5 \pm 5.3***	171.9 \pm 4.1***
Body mass, kg	76.7 \pm 10.8	73.7 \pm 7.3	74.4 \pm 8.2
BMI, $\text{kg}\cdot\text{m}^{-2}$	23.8 \pm 3.0	24.2 \pm 2.1	25.0 \pm 2.7
Body fat, %	17.1 \pm 5.2	26.1 \pm 4.7***	28.0 \pm 5.0***
Neuromuscular			
MVC KE, (N·m)· kg^{-1}	4.41 \pm 0.80	2.78 \pm 0.67***	1.84 \pm 0.49***.†††
MVC PF, (N·m)· kg^{-1}	1.70 \pm 0.47	1.45 \pm 0.41*	1.09 \pm 0.24***.†
MVC DF, (N·m)· kg^{-1}	0.59 \pm 0.19	0.57 \pm 0.17	0.44 \pm 0.16***.†
Aerobic			
Absolute $\dot{V}O_{2\text{max}}$, $\text{L}\cdot\text{min}^{-1}$	3.40 \pm 0.61	2.27 \pm 0.39***	1.67 \pm 0.28***.†††
Relative $\dot{V}O_{2\text{max}}$, $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	44.6 \pm 8.0	31.1 \pm 6.53***	22.7 \pm 4.8***.†††
VT1, $\text{L}\cdot\text{min}^{-1}$	1.89 \pm 0.33	1.35 \pm 0.22***	1.09 \pm 0.16***.†††
VT1, $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	24.9 \pm 5.0	18.5 \pm 4.2***	14.8 \pm 2.5***.†
VT1, % $\dot{V}O_{2\text{max}}$	55.9 \pm 6.6	60.2 \pm 6.7	63.1 \pm 16.5***.††
Resting $\dot{V}O_2$, $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	4.46 \pm 0.95	3.70 \pm 0.77***	3.10 \pm 0.51***.†
Balance			
Tandem eyes open, s	87.7 \pm 14.4	74.2 \pm 28.3	39.1 \pm 36.6***.†††
Tandem eyes closed, s	88.5 \pm 4.8	45.4 \pm 35.0***	13.5 \pm 21.2***.†††
Physical activity			
Steps per day	9867 \pm 2553	11,457 \pm 2962	10,357 \pm 3553
GPAQ, MET·min· wk^{-1}	3300 \pm 2553	3517 \pm 2286	3186 \pm 3859

Note that $n = 21$ for very old men because two VOM did not meet the $\dot{V}O_{2\text{max}}$ criteria.

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$: Significantly different from Young.

† $P < 0.05$, †† $P < 0.01$, ††† $P < 0.001$: Significantly different from Old.

BMI, body mass index; CoW, cost of walking; DF, dorsiflexors; GPAQ, Global Physical Activity Questionnaire; KE, knee extensors; MVC, maximal voluntary contraction; PF, plantar flexors; $\dot{V}O_{2\text{max}}$, maximal oxygen uptake; VT1, first ventilatory threshold.

The 95% confidence ellipse areas of the center of pressure were 86% and 173% higher in OM and VOM, respectively, compared with YM (all $P < 0.001$).

PA level was similar across the three groups with both GPAQ ($P = 0.77$) and accelerometer measurements ($P = 0.09$).

Cost of waking. Resting $\dot{V}O_2$ decreased significantly with age (all $P < 0.001$) with a 17% and 31% decrease for OM and VOM compared with YM, respectively (Table 1). Net CoW was not different among the three speeds for each group ($P = 0.32$; Fig. 2). Net CoW was significantly higher for OM and VOM (at PWS: 2.9 ± 0.7 and $3.7 \pm 0.5 \text{ J}\cdot\text{m}^{-1}\cdot\text{kg}^{-1}$, respectively; $P < 0.001$) compared with YM ($2.3 \pm 0.3 \text{ J}\cdot\text{m}^{-1}\cdot\text{kg}^{-1}$) with a more pronounced difference after 80 yr. Net CoW values at $1.11 \text{ m}\cdot\text{s}^{-1}$, $1.67 \text{ m}\cdot\text{s}^{-1}$, and PWS were 32% ($P < 0.001$), 19% ($P < 0.01$), and 26% ($P < 0.001$) higher in VOM compared with OM. Net CoW values at the same speeds were 27% ($P < 0.001$), 26% ($P < 0.01$), and 29% ($P < 0.001$) higher in OM compared with YM. There was no speed–group interaction ($P = 0.07$).

Gait parameters. Age-related differences were found for step frequency, but only VOM were higher than YM and OM for CVs of STM (Table 2). At $1.11 \text{ m}\cdot\text{s}^{-1}$, step frequency was higher in OM ($P = 0.009$) and VOM ($P = 0.001$), and CV of STM was higher only for VOM ($P < 0.001$) compared with YM. At $1.67 \text{ m}\cdot\text{s}^{-1}$, step frequency was higher in OM ($P < 0.001$) and VOM ($P < 0.001$), and CV of STM was higher only for VOM ($P = 0.03$) compared with YM. At PWS, step frequency was higher in OM ($P = 0.001$) and VOM ($P = 0.02$), and CV of STM was higher only for VOM ($P < 0.001$) compared with YM.

Walking performance. PWS of VOM ($1.17 \pm 0.22 \text{ m}\cdot\text{s}^{-1}$) was significantly slower than YM ($1.47 \pm 0.21 \text{ m}\cdot\text{s}^{-1}$; $P < 0.001$) and OM ($1.38 \pm 0.19 \text{ m}\cdot\text{s}^{-1}$; $P < 0.001$), and there was no difference between YM and OM ($P = 0.19$).

$\dot{V}O_2$ at PWS expressed as percentage of VT1 was lower in YM ($60.7\% \pm 20.8\%$) than in OM ($81.6\% \pm 20.0\%$; $P < 0.001$) and VOM ($103.7\% \pm 16.3\%$; $P < 0.001$), and same age-related differences were observed at $1.11 \text{ m}\cdot\text{s}^{-1}$ (YM: $47.5\% \pm 10.2\%$, OM: $72.0\% \pm 16.7\%$, VOM: $101.5\% \pm 18.7\%$; all $P < 0.001$) and $1.67 \text{ m}\cdot\text{s}^{-1}$ (YM: $70.6 \pm 11.6\%$, OM: $98.7 \pm 25.1\%$, VOM: $129.6 \pm 20.1\%$; all $P < 0.001$).

TABLE 2. Gait variability measurement for the three different speeds.

Variables	Young	Old	Very Old
$1.11 \text{ m}\cdot\text{s}^{-1}$			
Step frequency, steps per min^{-1}	98.5 ± 7.8	$110.5 \pm 10.7^{***}$	$114.9 \pm 29.9^{***,\dagger\dagger}$
CV, %	6.9 ± 1.2	7.6 ± 2.2	$9.8 \pm 2.7^{***,\dagger\dagger}$
PWS			
Step frequency, steps per min^{-1}	108.9 ± 7.1	$118.4 \pm 10.3^{***}$	$116.8 \pm 15.6^{**}$
CV, %	5.3 ± 1.4	6.0 ± 1.7	$8.2 \pm 3.0^{***,\dagger\dagger}$
$1.67 \text{ m}\cdot\text{s}^{-1}$			
Step frequency, steps per min^{-1}	114.3 ± 6.6	$123.6 \pm 8.7^{***}$	$130.1 \pm 12.2^{***}$
CV, %	5.4 ± 1.5	5.9 ± 1.8	$7.6 \pm 4.2^*$

* $P < 0.05$, *** $P < 0.001$: Significantly different from Young.

†† $P < 0.01$, ††† $P < 0.001$: Significantly different from Old.

CV, coefficient of variation.

Differences among very old men. No significant difference was found for any of the anthropometric parameters, such as body mass ($P = 0.17$), height ($P = 0.75$), BMI ($P = 0.13$), and body fat percentage ($P = 0.67$). MVC KE ($P < 0.47$) and MVC DF ($P < 0.001$) were significantly lower in VO_{slow} compared with VO_{fast} (Table 3), but no significant difference was observed for MVC PF between the two groups ($P = 0.44$). $\dot{V}O_{2\text{max}}$ ($P < 0.001$) and VT1 ($P < 0.001$) were lower in VO_{slow} compared with VO_{fast} . The number of steps per day ($P < 0.001$) and GPAQ score ($P = 0.03$) were lower in VO_{slow} compared with VO_{fast} .

No difference in CV of STM was found at PWS between VO_{fast} and VO_{slow} ($P = 0.33$). PWS was 21% lower in VO_{slow} than in VO_{fast} ($P = 0.01$; Fig. 3). No significant differences between the two groups were observed in either net CoW at $1.11 \text{ m}\cdot\text{s}^{-1}$ ($P = 0.23$) and PWS ($P = 0.50$; Fig. 4) or $\dot{V}O_2$ at PWS expressed as a percentage of VT1 (99.2% and 105.1% for VO_{slow} and VO_{fast} , respectively; $P = 0.45$).

Linear regressions. All linear regressions stratified by age and for all participants pooled together are reported in Table 4. For neuromuscular parameters, significant negative correlations were found between MVC KE and net CoW at $1.67 \text{ m}\cdot\text{s}^{-1}$ ($r = -0.88$, $P = 0.03$) and PWS ($r = -0.54$, $P = 0.02$) for VOM only. Significant negative correlations were found between MVC PF and net CoW at $1.67 \text{ m}\cdot\text{s}^{-1}$ for OM ($r = -0.46$, $P = 0.04$) and VOM ($r = -0.90$, $P = 0.04$). Regarding

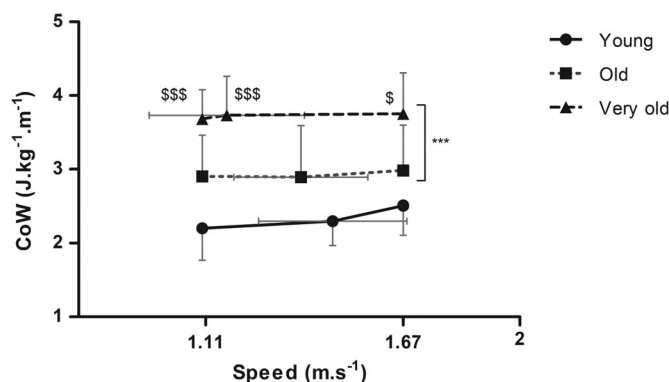


FIGURE 2—Net energy cost of walking (CoW) for young, old, and very old men at $1.11 \text{ m}\cdot\text{s}^{-1}$, $1.67 \text{ m}\cdot\text{s}^{-1}$, and preferred walking speed. Symbols between the speed of 1.11 and $1.67 \text{ m}\cdot\text{s}^{-1}$ represent the mean and SD of the preferred walking speed for each group. ***Significantly different from young men ($P < 0.001$); \$\$\$Significantly different from old men ($P < 0.05$ and $P < 0.001$, respectively).

TABLE 3. Characteristics of $\dot{V}O_{low}$ and $\dot{V}O_{high}$.

Variables	$\dot{V}O_{slow}$	$\dot{V}O_{fast}$
<i>n</i>	13	7
Anthropometric		
Age	84.9 ± 2.7	86.1 ± 2.3
Height, cm	171.0 ± 4.9	171.4 ± 3.0
Body mass, kg	76.9 ± 7.6	71.6 ± 9.0
BMI, kg·m ⁻²	25.9 ± 2.1	24.0 ± 3.2
Body fat, %	28.5 ± 5.2	27.4 ± 5.0
Strength		
MVC KE, (N·m)·kg ⁻¹	1.69 ± 0.44	2.16 ± 0.47*
MVC PF, (N·m)·kg ⁻¹	1.07 ± 0.26	1.13 ± 0.19
MVC DF, (N·m)·kg ⁻¹	0.37 ± 0.13	0.57 ± 0.08***
Aerobic		
$\dot{V}O_{2max}$, mL·kg ⁻¹ ·min ⁻¹	20.74 ± 5.12	25.42 ± 2.95***
VT1, mL·kg ⁻¹ ·min ⁻¹	10.56 ± 6.40	16.61 ± 2.42***
Functional		
6MWT, m	438.4 ± 70.4	563.3 ± 36.7***
TUG, s	8.35 ± 1.32	5.56 ± 1.00***
Physical activity		
Steps per day	8598 ± 2391	13,256 ± 2761***
GPAQ	1805 ± 1991	4800 ± 5293*

Note that *n* = 20 because two very old men did not meet the $\dot{V}O_{2max}$ criteria and one very old man's RER was greater than 1.

P* < 0.05, *P* < 0.01, ****P* < 0.001: Significantly different from $\dot{V}O_{slow}$.

6MWT, 6-min walking test; DF, dorsiflexors; KE, knee extensors; MVC, maximal voluntary contraction; PF, plantar flexors; PWS, preferred walking speed; TUG, Timed-Up-and-Go; $\dot{V}O_{2max}$, maximal oxygen uptake; VT1, first ventilatory threshold.

gait parameters, significant positive correlations were found between step frequency and net CoW at 1.11 m·s⁻¹ (*r* = 0.42, *P* = 0.02) and PWS (*r* = 0.79, *P* < 0.001) for OM. Similar results were found for VOM, as significant positive correlations between step frequency and net CoW were observed at 1.11 m·s⁻¹ (*r* = 0.52, *P* = 0.01) and 1.67 m·s⁻¹ (*r* = 0.87, *P* = 0.02). Significant positive correlations were observed between CV of STM and net CoW at 1.11 m·s⁻¹ (*r* = 0.37, *P* = 0.04) for OM. For VOM, similar correlations were found at 1.11 m·s⁻¹ (*r* = 0.65, *P* = 0.02), 1.67 m·s⁻¹ (*r* = 0.91, *P* = 0.01), and PWS (*r* = 0.48, *P* = 0.03) for VOM. A significant and positive correlation was found between PWS and net CoW at PWS for YM (*r* = 0.41, *P* = 0.01). In contrast, the correlations were negative for VOM (*r* = -0.56, *P* = 0.01) and for all groups pooled together

(*r* = -0.32, *P* = 0.003). Significant positive correlations were also observed between PWS and $\dot{V}O_2$ at PWS when expressed as percentage of VT1 for YM (*r* = -0.81, *P* < 0.001), but the *P* value did not reach the significance level for OM (*r* = 0.35, *P* = 0.07) and VOM (*r* = 0.46, *P* = 0.05). Regarding PA, significant positive correlations were found between GPAQ score and PWS for OM (*r* = 0.44, *P* = 0.02) and VOM (*r* = 0.47, *P* = 0.03). Significant positive correlation was observed between steps per day and PWS for OM (*r* = 0.41, *P* = 0.03).

No correlation was found between MVC DF and net CoW at any speed, or between MVC DF and PWS. No correlations were found between balance tests (i.e., time maintained during TEO and TEC) and net CoW at any speed. Significant positive correlations were observed between the time maintained during TEO and PWS for OM (*r* = 0.38, *P* = 0.04) and for all groups (*r* = 0.51, *P* < 0.001), but the *P* value for VOM did not reach the level of significance (*r* = 0.42, *P* = 0.06). No correlation was observed between any of the posturographic parameters and net CoW or PWS.

DISCUSSION

The purpose of the present study was to investigate the age-related changes in CoW and PWS in men, especially after the age of 80. This study also aimed at examining the parameters associated with both net CoW and PWS in young, old, and very old adults. Whereas previous studies have focused on aerobic capacities, neuromuscular function, or gait patterns separately, the present study is the first to examine the change in net CoW throughout lifespan using an integrative approach. The main results are that (i) net CoW increased with age, with a greater increase after 80 yr old, whereas PWS decreased only after 80 yr old; (ii) the main parameters associated with net CoW, among the measured parameters, were step frequency and CV of STM in old adults, whereas the decrease in KE and PF MVC also contributed to the greater deterioration in

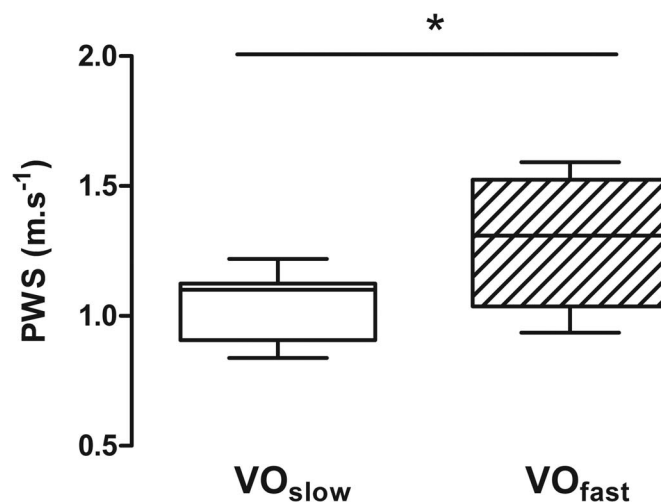


FIGURE 3—Preferred walking speed (PWS) for $\dot{V}O_{slow}$ (very old men who did not complete the walk at 1.67 m·s⁻¹) and $\dot{V}O_{fast}$ (very old men who completed the walk at 1.67 m·s⁻¹). The boxes represent the first and third quartiles, and the line inside the boxes represents the median. The minimum and maximum values are reported by upper and lower segments. **P* < 0.05: Significantly different from $\dot{V}O_{slow}$.

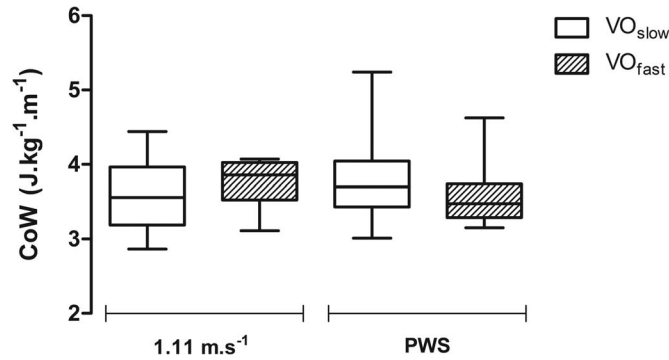


FIGURE 4—Net energy cost of walking (CoW) at 1.11 m·s⁻¹ and preferred walking speed (PWS) for (very old men who did not complete the walk at 1.67 m·s⁻¹) and VO_{fast} (very old men who completed the walk at 1.67 m·s⁻¹). The boxes represent the first and third quartiles, and the line inside the boxes represents the median. The minimum and maximum values are reported by upper and lower segments.

net CoW after the age of 80, especially at high speed; and (iii) PWS was mainly related to the level of PA in old and very old adults.

Cost of walking. Compared with YM, CoWs at PWS were 26% and 62% higher in OM and VOM, respectively. Similar age-related differences were observed at 1.1 and 1.67 m·s⁻¹. In a meta-analysis, a 17% difference in CoW was observed between healthy young (18–41 yr) and older (≥59 yr) adults (2). Whereas our results had a slightly greater magnitude, likely due to different mean age, the difference between OM and YM in our study fell within the 95% confidence interval calculated in the meta-analysis. If the onset of the CoW increase becomes apparent after the sixth decade (30,31), three studies have identified a more pronounced rise in CoW after 80 yr old (9,30,31), as also found in the present study. The 67%, 50%,

and 62% higher net CoW at 1.11 m·s⁻¹, 1.67 m·s⁻¹, and PWS for VOM versus YM in the present study exceeded the 22% greater CoW averaged from speeds ranging from 0.67 to 1.56 m·s⁻¹, and that of 28% at PWS observed by Malatesta et al. (9). Given the marked increase in CoW after 80 yr old (30), the older age in our sample may explain the discrepancy between the studies. After the age of 80, even small age differences can have a significant impact on the functional capacity of older people, especially when differences in PA levels are considered. Indeed, methodological factors such as different PA levels or sex differences (only men vs majority of women) in the study of Malatesta et al. (9), as well as differences in the PWS of YM in the two studies may also explain the discrepancy.

In the present study, a simple linear regression stratified by age was used to investigate the mechanisms of age-related

TABLE 4. Pearson correlation analysis for young men (YM), old men (OM), very old men (VOM), and all subjects pooled together.

Strength	MVC KE				MVC PF			
	YM	OM	VOM	All	YM	OM	VOM	All
CoW at 1.11 m·s ⁻¹	-0.27	-0.14	-0.07	-0.70*	-0.40*	0.03	0.18	-0.45*
CoW at PWS	-0.13	0.00	-0.54*	-0.62*	-0.12	0.12	-0.33	-0.37*
CoW at 1.67 m·s ⁻¹	-0.16	0.23	-0.88*	-0.50*	-0.45*	0.46*	-0.86*	-0.28*
PWS	-0.22	0.48*	0.30	0.42*	-0.13	0.05	0.14	0.23*
Aerobic	VO _{2max}				VT1			
	YM	OM	VOM	All	YM	OM	VOM	All
CoW at 1.11 m·s ⁻¹	-0.23	-0.28	-0.01	-0.69*	-0.20	-0.23	0.20	-0.60*
CoW at PWS	-0.14	-0.19	0.22	-0.60*	-0.20	-0.09	0.00	-0.55*
CoW at 1.67 m·s ⁻¹	0.09	-0.23	-0.10	-0.48*	0.10	-0.21	0.36	-0.39*
PWS	-0.30	0.17	0.27	0.30	-0.30	0.17	0.21	0.30*
Gait Parameters	Step Frequency				CV of STM			
	YM	OM	VOM	All	YM	OM	VOM	All
CoW at 1.11 m·s ⁻¹	0.13	0.42*	0.52*	0.44*	0.22	0.37*	0.65*	0.59*
CoW at PWS	-0.14	0.79*	0.26	0.61*	0.14	0.36	0.48*	0.57*
CoW at 1.67 m·s ⁻¹	0.23	0.24	0.87*	0.54*	0.06	0.05	0.91*	0.22
PWS	0.55***	0.46*	0.53*	0.23*	-0.19	-0.25	-0.19	-0.38*
Physical Activity	GPAQ				Steps per Day			
	YM	OM	VOM	All	YM	OM	VOM	All
CoW at 1.11 m·s ⁻¹	-0.22	-0.31	-0.15	-0.14	-0.07	-0.40*	0.23	-0.02
CoW at PWS	-0.26	-0.12	0.00	-0.01	-0.07	-0.02	-0.20	-0.04
CoW at 1.67 m·s ⁻¹	-0.24	-0.15	-0.16	0.03	-0.09	-0.03	0.40	0.34*
PWS	-0.32*	0.44*	0.47*	0.13	0.05	0.41*	0.42	0.23*

*Indicates that the Pearson correlation coefficient is statistically significant at $P < 0.05$.

Note: A single threshold for the critical alpha value, i.e., $P < 0.05$, was used to improve clarity.

CoW, energy cost of walking; CV, stride mean time coefficient of variation; GPAQ, Global Physical Activity Questionnaire; KE, knee extensors; MVC, maximal voluntary contraction; PF, plantar flexors; PWS, preferred walking speed; STM, stride mean time; VO_{2max}, maximal oxygen uptake; VT1, first ventilatory threshold.

increase in CoW. Multiple linear regression analysis was not considered because nearly all physiological parameters are altered with aging, potentially introducing errors in the interpretation of specific correlations involving a wide range of ages. In YM, net CoW showed a negative correlation with MVC PF only, suggesting that individuals with a lower plantar flexor strength exhibit greater net CoW due to a limited push-off phase. During walking, the greatest mechanical power among the joints is produced at the ankle, which exerts a pronounced burst late in the stance phase, referred to as push-off (51). Insufficient ankle push-off requires greater hip extensor power to redirect and accelerate the body's center of mass, which is associated with the increase in CoW (13). The impulse has to be applied just before heel strike in order to reduce dissipative work during ground collision (52). Accordingly, ankle push-off appears to be key factor in CoW. In older adults, the lack of correlation between net CoW and MVC PF at lower speeds may be due to age-related changes in force/power production at the ankle level during walking. This results in a decrease in the push-off phase and a significant reliance on the hip muscles to compensate (53,54), as suggested by the previously shown distal-to-proximal shift in muscle workload with advancing age (13,53). Therefore, the reduction in power during the push-off phase in older adults lowers the contribution of PF force in the increase in CoW. However, a strong negative correlation between net CoW and MVC PF was observed at high speed in VOM. As speed increases, PF become more involved because hip compensation alone is not sufficient to walk at $1.67 \text{ m}\cdot\text{s}^{-1}$. As a result, a higher MVC PF can restrict hip compensation and, in turn, limit the increase in CoW. Surprisingly, a positive correlation was observed between MVC PF and net CoW in OM at high speed. Further investigation is needed to clarify this unexpected result. Due to a greater neuromuscular alterations in VOM, characterized by an accelerated decline in both muscle quantity and quality (6), the greater relative strength required to walk in VOM compared with OM (55), especially at high walking speeds, may result in a greater fast-twitch fibers recruitment, which have been shown to be less economical than slow-twitch fibers (56). This could also explain the correlation observed between MVC KE and net CoW in VOM. Malatesta et al. (9) reported a significant correlation between MVC KE and CoW when all three groups were pooled. However, as explained above, age may act as a confounding factor when correlating CoW and MVC KE (as well as other variables) across a broad range of age. The present study offers further insights in the relationship between neuromuscular function, CoW and age. However, walking involves dynamic muscle contractions, i.e., power, rather than isometric contractions in the lower limbs. As power is the product of force by speed, our results only capture part of the relationship between muscle dynamics and metabolic cost.

Although walking above VT1 could induce an additional O_2 consumption, i.e., slow component, or provide an intensity high enough to recruit fast-twitch fibers, no relationships were found between aerobic parameters such as $\dot{V}\text{O}_{2\text{max}}$ and VT1 and net CoW.

Step frequency increased with age at each speed. Correlations between step frequency and net CoW were observed for both OM and VOM at each speed, suggesting that individuals with higher step frequency consume more energy per distance covered. This change in walking pattern may be due to an alteration in the power generation during the push-off phase of the plantar flexors, as discussed previously and as widely reported in the literature (7,8,28,53,57–62). Within the typical range of walking speeds (approximately up $2.4 \text{ m}\cdot\text{s}^{-1}$), there is a specific step frequency associated with only one step length that minimizes energy expenditure per unit of distance traveled (63). The age-related decrease in step length due to the decrease in strength and balance may induce a change in step frequency to minimize the CoW in older adults. However, given the age-related impairment in the neuromuscular system, a mismatch between step length and step frequency may result in an increased CoW in older adults. Further studies manipulating step frequency in older adults should be conducted to check this hypothesis. The age-related increase in step frequency is multifactorial and may involve limitations in muscle power at the level of the plantar flexors and hips, greater joint stiffness, and the adoption of a cautious gait to enhance stability.

Gait variability may also lead to a deteriorated CoW. The rhythmic movement of “normal” gait has a nominal periodic pattern, small step-by-step variations and is energetically economical (17). Age-related changes in the sensory system such as photoreceptors, vestibular organs, muscle spindles, and other proprioceptors (64) contribute to the deviations from this pattern and thus may lead to increased gait variability and additional energy cost. Age-related disturbances (e.g., impaired balance or sensory inputs) would result in additional muscular adjustments to stabilize the “normal” gait pattern and could explain the age-related increase in CoW with age. In the present study, correlations were found between CV of STM and net CoW in OM and VOM. CV of STM, which serves as an index of gait variability, emerged as a significant contributor to the variance in net CoW for OM at low speed and for VOM at all speeds. A variability–speed relationship could potentially increase gait variability in OM (65). Indeed, a reduction in walking speed induced an increase in gait variability. This hypothesis can be supported by our results showing an increase in CV of STM with decreasing speed for all groups. Greater deteriorations of the sensory and vestibular system after 80 yr (66), as evidenced by the age-related alteration in balance tasks performance (TEO and TEC), may result in disturbances in foot placement during walking and challenges in actively controlling balance due to feedback alterations. Gait variability appeared to be a major factor associated with net CoW in VOM. However, no correlation was found between net CoW and balance tasks performance.

Walking performance. Compared with YM, PWS was 6% lower in OM and 15% lower in VOM, in accordance with the literature (26,67). However, the PWS found in the present study was higher than the reference values obtained on approximately 4500 individuals (OM: 1.38 vs $1.18 \text{ m}\cdot\text{s}^{-1}$; VOM: 1.17 vs $1.02 \text{ m}\cdot\text{s}^{-1}$) by Dommershuijsen et al. (23). The discrepancy

may be due to healthier participants in the present study or to discrepancies in the method used to assess PWS (68).

In accordance with the literature, MVC KE was correlated with PWS in OM (27,69,70). At the KE level, several studies reported greater peak power and work absorption in older adults before and after PF power generation (71). A higher KE MVC may facilitate greater energy transfer from the knee to the hip via the rectus femoris, resulting in increased hip flexor force to initiate the leg into swing. Similarly, a greater strength in the hip flexors muscles (not measured in the present study) may compensate for the change in ankle push-off by pulling the leg forward to assist with swing initiation (58,71), thereby reducing the decline in step length. As the age-related decrease in PWS was associated with a reduction in step length (57), restricting the decline in step length would contribute to maintaining PWS. In addition, the difference in PWS between YM and VOM may be due, in part, to the significant difference in height. Indeed, low height has been associated with lower step length and PWS (72).

A small sample size or a possible curvilinear relationship (suggesting a critical threshold, below which strength significantly influences PWS, and beyond which strength has a minimal impact on PWS) between PWS and strength (73) could explain the weak to moderate relationship in OM and the surprising lack of correlation between MVC KE and PWS in VOM. The absence of correlation has been previously observed (74). The VOM group exhibited significant heterogeneity, as evidenced by significant differences in TUG and 6MWT in VOM_{high} and VOM_{low}, potentially masking an association between strength and PWS. For VOM, these findings may suggest that the determinants of walking speed may vary depending on the degree of VOM impairment and may include factors other than strength alone. Moreover, power may play a greater role than strength in the age-related reduction in walking speed (27). The absence of correlation between MVC PF and PWS was unexpected as impairments of the PF appeared to be a key factor in the age-related reduction in stride length and increase in double support time, both factors being associated with speed decline in older adults. (57). As discussed previously for CoW, the hip may compensate for PF impairment, but this relationship becomes more apparent at higher speeds when the PF are actively engaged.

The age-related increase in CoW may contribute to the decline in PWS. According to recent studies, CoW at PWS closely reflects the decline in walking speed (30,31). However, the present study has shown that this was only true for VOM, as OM exhibited higher net CoW but similar PWS compared with YM. A slower walking speed may be a compensatory mechanism to counteract the increase in energy demand associated with aging in order to avoid reaching metabolic stress levels that induce high levels of fatigability, which could explain the negative correlation between net CoW and PWS in VOM (31). This correlation was not significant for OM (contrary to the findings of Schrack et al. (27)) and was even positive for YM, which was not expected. Some YM may have overestimated their PWS, which induced a rise in net CoW due to the U-shaped

relationship between CoW and walking speed. Indeed, a systematic review reported a constant PWS of $1.38 \text{ m}\cdot\text{s}^{-1}$ in healthy individuals between the ages of 18 and 49 yr (75), a value slightly lower than the one observed in the present study ($1.47 \text{ m}\cdot\text{s}^{-1}$). The decline in VT1 associated with aging, coupled with the simultaneous age-related rise in CoW, may contribute to a reduction in functional reserve defined as the available energy minus energy demand. Nevertheless, compared with YM, OM exhibited a similar PWS and a higher net CoW. A superior level of aerobic fitness in OM compared with VOM may help in maintaining the functional reserves of OM at a sufficient level to walk at the same PWS than YM. Again, the hypothesis of a nonlinear relationship between CoW and VT1 appears plausible.

PA measured by questionnaire was positively correlated with PWS for OM and VOM, which was expected due to the beneficial effects of PA on aerobic and neuromuscular capacities (76). Despite the different measured outcomes (i.e., perception vs objective activity), a similar trend was observed when PA was quantified using an accelerometer. However, there is a consensus in the literature that habitual aerobic PA (i.e., walking and running) does not avoid the age-related changes in walking pattern, including the distal-to-proximal shift and increase in step frequency (60,61,77–80). In addition, PA does not preclude the neurodegenerative processes contributing to gait variability, ultimately resulting in a reduction in step frequency. Indeed, aerobic PA does not contribute to slowing the age-related decline in lower limb strength/power (81). However, in the present study, older adults who maintained a high level of PA showed similar PWS than young adults, suggesting that PA may limit some of the age-related impairments. The age-related change in CoW induces an increase in the energy expenditure and, coupled with the alteration in the cardiovascular function, could force older adult to walk near their maximal aerobic capacity. Therefore, aerobic exercise, the primary type of PA in older adults, enhances functional reserve by increasing VT1 and $\dot{V}O_{2\text{max}}$, enabling active older adults to maintain higher PWS despite the age-related rise in the CoW.

Differences among very old participants. During the assessment of net CoW, 13 out of the 20 VOM were unable to perform the $1.67 \text{ m}\cdot\text{s}^{-1}$ trial (VO_{slow}). The two subgroups did not differ in terms of age and anthropometric parameters. All aerobic and neuromuscular parameters but MVC PF were greater for those who successfully performed the $1.67 \text{ m}\cdot\text{s}^{-1}$ walk (VO_{fast}). MVC KE was associated with the time taken to sit-to-walk during the TUG test (82), a common clinical assessment to screen for mobility impairment and fall risk in older adults. Even if the VO_{slow} did not reach the threshold of risk of falling, i.e., 14 s (83), a shorter time to perform the TUG symbolized less functional impairment. Despite greater strength and aerobic capacity in VO_{fast} compared with VO_{slow} , net CoW was not different between the two groups, suggesting that these capacities do not play a key role in the age-related increase in CoW at very old age. Still, VO_{fast} had a higher PWS. Higher aerobic parameters in VO_{fast} , probably due to higher PA levels, may improve the physiological reserves of VO_{fast} , allowing VO_{fast} to have a higher PWS compared with

their less active counterparts, while remaining within their energy availability limits. Indeed, $\dot{V}O_2$ at PWS as a percentage of VT1 was not different between VO_{slow} and VO_{fast} , suggesting that both VO_{slow} and VO_{fast} regulated their PWS to maintain $\dot{V}O_2$ around VT1. Low VT1 in VO_{slow} and high energy expenditure due to the age-related increase in net CoW induced a reduction in their PWS. Indeed, higher aerobic fitness levels, as indicated by higher $\dot{V}O_{2max}$ and VT1, allowed VO_{fast} to maintain PWS at higher speeds, close to the PWS of the OM group. For VO_{slow} , lowering the metabolic expenditure (i.e., reducing PWS) is likely a strategy to stay within the limits of energy availability (35). Measuring PWS is important because a high PWS is related to a better autonomy and better quality of life but also because PWS is considered as being the sixth vital sign (84), reflecting functional ability and having the potential to predict future health status.

Limitations. Although our sample of older adults exhibited heterogeneity in functional capacity, as evidenced by the results of the TUG and 6MWT in VOM, the overall average PA levels may not be representative of the elderly population. VOM showed a large number of steps per day, similar to YM and OM, which was not expected. Also, the static balance test may not be sufficiently discriminative to explain the age-related increase in net CoW. In addition, step width, recognized as a factor contributing to the greater CoW in older adults (59), was not measured in the present study. A more in-depth biomechanical analysis was not possible due to the lack of separate force plates to differentiate left and right forces during the double contact phase. This could have provided important information about the deteriorated CoW in older adults. Because assessment of muscle contraction efficiency and antagonist activation are factors involved in the age-related increase in CoW, measuring these parameters together

with the parameters assessed in the current study would allow a comprehensive examination of the mechanisms involved in the greater CoW in aging populations. In addition, $\dot{V}O_{2max}$ and VT1 were determined during an incremental test using an ergocycle and can lead to an underestimation of these parameters compared with a treadmill test (85).

The duration of the net CoW assessment may appear short. However, as explained in the Methods section, a 2-min familiarization period before the 4-min dedicated to net CoW assessment, combined with a visual inspection, ensured that all participants reached the necessary 1-min plateau required for accurate net CoW calculation.

CONCLUSIONS

The present study showed an age-related increase in energy CoW, with a more pronounced rise after the age of 80, an age that also correspond to the decrease of PWS. A deteriorated net energy cost of locomotion in very old men was mainly associated with step frequency (average and variability) and maximal strength of lower limbs extensors muscles (especially at high speed), suggesting a predominant influence of impairments in the vestibular (although not measured in the present study) and neuromuscular systems. This could force very old adults to maintain exercise intensity below a certain level, possibly reducing their autonomy. Maintaining a high level of PA potentially delays the age-related decline in walking speed.

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