Aerobic Capacity Determines Habitual Walking Acceleration, Not Electromyography-Indicated Relative Effort

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Objective: Habitual walking is important for health and can be measured with accelerometry, but accelerometer does not measure physiological effort relative to capacity. We compared accelerometer-measured absolute intensity and electromyography (EMG)-measured relative muscle activity between people with low versus excellent aerobic fitness levels during their habitual walking. Methods: Forty volunteers (19 women; age 49.3 ± 17.1 years, body mass index 24.0 ± 2.6 kg/m²; peak oxygen uptake 40.3 ± 12.5 ml/kg/min) wore EMG-shorts and a hip-worn accelerometer simultaneously for 11.6 ± 2.2 hr on 1.7 ± 1.1 days. Continuous gait bouts of at least 5-min duration were identified based on acceleration mean amplitude deviation (MAD, in milli gravitational acceleration, mg) and mean EMG amplitude, with EMG normalized to maximal isometric knee extension and flexion (EMG, in percentage of maximal voluntary contraction EMG). Peak oxygen uptake was measured on a treadmill and maximal strength in isometric leg press (leg press max). MAD and EMG were compared between age- and sex-specific fitness groups (low-average, good, and excellent) and in linear models. Results: During habitual walking bouts (4.1 ± 4.1 bouts/day, 0.9 ± 1.0 min/bout), the low-average fit participants had an approximately 28% lower MAD (245 ± 64.3 mg) compared with both good fit and excellent fit participants (313 ± 68.1 mg, p < .05), but EMG was the same (13.1% ± 8.42% maximal voluntary contraction EMG, p = .10). Absolute, relative to body mass, and relative to skeletal muscle mass peak oxygen uptake (but not leg press max) was positively associated with MAD independent of age and sex (p < .01), but there were no associations with EMG. Conclusions: People with low-average aerobic capacity habitually walk with a lower accelerometer-measured absolute intensity, but the physiological stimulus for lower-extremity muscles is similar to those with excellent aerobic capacity. This should be considered when measuring and prescribing walking for health.

Keywords: gait, accelerometer, muscle activity, wearable, aerobic fitness, physical activity

The updated physical activity guidelines by the World Health Organization emphasize that even short physical activity bouts, of any intensity, matter for health (World Health Organization, 2020). The guidelines also emphasize that a greater activity intensity is more beneficial for health, with moderate to vigorous activity bringing considerable benefits (World Health Organization, 2020). Physical activity intensity can be measured with various methods. Accelerometry enables measuring dynamic physical activity intensity accurately over long periods with a low participant burden (Matthews, 2005). However, accelerometer-measured physical activity intensity lacks consideration for an individual’s fitness level. People with a high aerobic fitness level have more moderate and vigorous physical activity and are more likely to meet the current physical activity guidelines defined as 150 min/week of moderate to vigorous physical activity when estimated with accelerometer (Dyrstad et al., 2016; Vaara et al., 2020). When the activity volume is considered relative to maximal fitness, people with high and low aerobic fitness levels have a more similar activity profile (Kujala et al., 2017). Therefore, guidance to increase moderate to vigorous physical activity should consider the aerobic fitness level of an individual.

Walking is the most common form of physical activity. It is safe, easy to integrate into everyday life, and reduces the risk of cardiovascular diseases (Morris & Hardman, 1997; Oja et al., 2018). Because walking is a familiar activity for many, the guidance to increase walking intensity may be easier to communicate and implement, than guidance to increase moderate to vigorous activity. Like accelerometer-measured physical activity intensity, also walking intensity is affected by aerobic fitness level. Those with a higher maximal aerobic fitness require a smaller relative to maximum oxygen uptake at a given walking speed in lab conditions (Browning & Kram, 2005; Browning et al., 2006; Cunningham et al., 1982; Ozemek et al., 2013). In field conditions, terrain and climbing angle are changeable, and other factors like motivation or habit of walking may be different from lab conditions, and lab-measured results may not be generalizable to normal daily life. Less is known how aerobic fitness is associated with habitual walking intensity, and hence whether those with a higher aerobic fitness level would be more likely to reach the World Health Organization physical activity targets with their habitual walking.

One little studied potential determinant of free-living walking intensity is lower-extremity strength. Lower-extremity muscle strength is associated with a faster time to walk 400 m at a steady pace (Marsh et al., 2006), and strength improving interventions have increased maximal walking speed on a 6-m track and decreased relative to maximum muscle activity in functional tests in independently living elderly individuals (Hunter et al., 1995). While these studies highlight the importance of muscle strength on walking performance in older adults in controlled conditions, the associations of muscle strength with actual absolute or relative to maximum walking intensity during daily life remain unknown.
Absolute physical activity intensity estimation can be supplemented and detailed with physiological monitors, like heart rate monitors or electromyography (EMG). When individual calibration is used, such approaches can significantly improve physical activity energy expenditure and/or intensity estimation accuracy (Moon & Butte, 1996; Strath et al., 2001; Tikkanen et al., 2014). While accelerometer and heart rate monitor combinations are used to assess systemic energy expenditure and intensity, EMG recordings give information on the physical activity intensity at the muscle level (Finni et al., 2007; Tikkanen et al., 2013, 2014). A standard procedure in EMG analysis is to normalize the signal to maximal voluntary EMG activity of a given muscle group, which enables reliable and biologically meaningful comparison of muscle activity between individuals and activities (Knutson et al., 1994; Yang & Winter, 1984). Therefore, another advantage of EMG is that it provides a relative to fitness measure of intensity at the muscle level. Despite the potential significance of aerobic fitness on absolute walking intensity, less is known how aerobic fitness or muscle strength are associated with EMG-derived relative to maximum muscle activity during habitual walking.

This study aims to compare actigraphy-based habitual walking bout absolute intensities between groups of low-average and excellent peak oxygen uptake (VO2max) groups (primary outcome). We hypothesize that those with low-average VO2max have a lower accelerometry-derived absolute intensity during their habitual walking as compared with those with an excellent VO2max. Furthermore, we explore if EMG shorts-monitored habitual walking bout relative to maximum muscle activity is associated with aerobic fitness or with lower-extremity muscle strength (exploratory outcomes).

Materials and Methods

Data for this study were collected in the EMG24 project, which quantified muscle loading during normal daily life from healthy adults (Tikkanen et al., 2013). The participants were recruited by delivering advertisements to public places and different workplaces. A total of 245 individuals who responded were initially screened for eligibility based on having no reported chronic diseases affecting daily ambulatory activity and women not being pregnant. Daily EMG activity was measured from 109 eligible participants. Participants were excluded for (a) inability to sync actigraphy acceleration and EMG signal due to missing signal, artifacts or other reasons (total excluded n = 48); (b) inability to recognize walking bouts from the activity signal (n = 51); (c) not having EMG from treadmill test (n = 31); and (d) not having VO2 data (n = 30). The final sample for the present study was a total of 40 participants who had artifact-free EMG data from a minimum of one day period (≥8 hr recording time; Pesola et al., 2015), who were measured for VO2, and those who had valid walking acceleration data from a period corresponding to the valid EMG data. The study protocol was accepted by the ethics committee of University of Jyväskylä (2.4.2008), and participants signed an informed consent prior to the measurements. The Declaration of Helsinki was followed. The funding organizations had no role in the collection of data, analysis, and interpretation, and in the right to approve or disapprove publication of the finished manuscript.

The study protocol consisted of laboratory visits and measurements during daily life. Preceded by 12-hr fasting, height, weight, waist circumference, and body composition (InBody 720; InBody, Seoul, South Korea) were measured at the laboratory. Waist circumference was measured while participants were standing with their feet shoulder width apart. The top of the crest of ilium at the side of the waist was located, and the measurement tape was wrapped around the waist. The bottom of the measurement tape was aligned with the top of the crest of ilium and parallel to the floor along the entire length. Height and weight were measured twice and waist circumference three times, and the means were used for further analysis. After the fasting measurement participants were given breakfast, and the accelerometers and EMG shorts were worn with the guidance of a researcher. After a warm-up, maximal voluntary contractions (MVC) were completed and free-living assessments started. Participants visited the laboratory every morning to initiate the free-living measurement because the EMG shorts could log data for only one day at a time. On a separate day, maximal aerobic fitness was measured on a treadmill. Participants older than 45 years were screened by a medical doctor before the test.

Maximal Voluntary Contraction

After a warm-up including walking on a treadmill, walking stairs, and squatting with body weight (total warm-up duration 10–20 min), the participants were allowed to familiarize themselves with the isometric leg press dynamometer (Department of Biology of Physical Activity, University of Jyväskylä, Finland) at a knee angle of 107°, and subsequently, three to five maximal efforts were recorded with verbal encouragement. If torque increased more than 5% in the third attempt, more trials were done. The peak torque produced on any of the efforts is reported as the maximal lower-extremity strength result (leg press max). Subsequently, a similar protocol was used to measure maximal voluntary EMG activity in knee flexion/extension machine (David 220; David Health Solutions Ltd., Helsinki, Finland) with a knee angle of 140° in both flexion and extension, and subsequently, three to five maximal efforts were recorded with verbal encouragement. If torque increased more than 5% in the third attempt, more trials were done. The peak EMG amplitude produced on any of the efforts was used for EMG normalization (knee extension for quadriceps normalization; knee flexion for hamstring normalization).

VO2max and Treadmill Walking

The incremental treadmill (OJK-1; Teliniehtymä, Kotka, Finland) test consisted of 3-min loads starting at 4 km/hr walking and progressing at 1 km/hr speed increments until 7 km/hr. The 5 km/hr load was performed both at a level and with a 4° decline and incline. After the 7 km/hr level load, the test continued at 8° inclination at 5 km/hr and progressed to 10° inclination at 7 km/hr, which was continued until exhaustion (Tikkanen et al., 2014). The breath-by-breath results (Jaeger Oxycon Pro with the LabManager version 3.0 software; Viasys Healthcare GmbH, Hochberg, Germany) were averaged in nonoverlapping 30-s epochs, and the highest 30 s from the whole incremental test is reported as the VO2max value, that is, as maximal aerobic fitness.

Electromyography

The EMG shorts are equipped with textile EMG electrodes for measuring muscle activity from the quadriceps femoris and the hamstring muscles bilaterally (Myontec Ltd, Kuopio, Finland and Suunto Ltd, Vantaa, Finland; Figure 1). The EMG shorts produce a valid signal of muscle activity amplitude (Finni et al., 2007), produce repeatable results at laboratory and during normal daily life (Finni et al., 2007; Pesola et al., 2014), and can be used to estimate energy expenditure more accurately than accelerometer
and HR monitor, especially at low-intensity activities (Gao et al., 2019; Tikkanen et al., 2014). Four different sizes of shorts (XS, S, M, and L) were used to ensure electrodes lie tightly on the skin. Electrolyte gel (Electrolyte Creme REDUX; Parker Laboratories, Inc., Fairfield, NJ) was applied onto the electrode surfaces before they were put on. A small electronic module on the anterior waist contains signal amplifiers, a microprocessor with embedded software, data memory, and a computer interface. In the module, the EMG signal is measured in its raw form with a sampling frequency of 1000 Hz and a frequency band 50–200 Hz (−3 dB) and is first rectified and then averaged over 100-ms nonoverlapping intervals. The averaged data were stored in ASCII format in the memory of the module from which the data were downloaded to a computer (Myontec Ltd., Kuopio, Finland).

**Accelerometer**

The participants wore an accelerometer (two-axial, ±2.7 g, 8-bit a/d, sampling at 75 Hz, bandwidth 0–20 Hz, Alive Heart Monitor; Alive Technologies Pty Ltd, Arundel, QLD, Australia; Figure 1) on the hip just below the iliac crest using an elastic belt.

**Aerobic Fitness Groups**

Age- and sex-specific relative to bodyweight aerobic fitness norms (VO₂max; in milliliters per kilogram per minute) were used to categorize participants in low-average fit, high fit, and excellent fit groups (Shvartz & Reibold, 1990). Each individual was assigned the aerobic fitness category based on age- and sex-specific threshold values. For example, the average fitness level was assigned for 20- to 24-year-old men having VO₂max between 44 and 50 ml/kg/min, and for 20- to 24-year-old women having VO₂max between 37 and 41 ml/kg/min. For 50- to 54-year-old men average fitness category corresponded to VO₂max values between 33 and 36 ml/kg/min, and for 50- to 54-year-old women to 26–29 ml/kg/min. Individuals with a very poor (n = 2), poor (n = 2), fair (n = 3), and average aerobic fitness level (n = 4) formed the low-average fitness category.

**EMG Analyses**

The EMG data logger calculated the root mean squared value of each of the four channels over nonoverlapping 100-ms epochs, and thus 10 values per second per channel were recorded on a memory card. The EMG data were checked visually for artifacts and the corresponding data periods were manually removed from every channel in MegaWin software (Mega Electronics Ltd., Kuopio, Finland; Tikkanen et al., 2013). Using a custom-made MATLAB (version 7.11.0.587; MathWorks Inc., Natick, MA) algorithm, the baseline shift was minimized by applying a sliding 5-min minimum filter channel by channel on the 100-ms root mean squared values, which successfully removes nonphysiological baseline shift (Pesola et al., 2014). The mean of the channels was calculated to produce a one-dimensional array for the duration of the gait bout, and then the mean value of the one-dimensional array was recorded as the habitual walking EMG result of a given bout after synchronization with acceleration data (see below).

![Figure 1](image-url) — Example of synchronized EMG and MAD signals. EMG = electromyography; MAD = mean amplitude deviation.
Acceleration Analyses and Gait Bout Identification

The resultant acceleration was calculated for each sample and used for further analyses. Five-second nonoverlapping mean amplitude deviation (MAD; Vähä-Ypyä et al., 2015) values were then calculated and subsequently filtered with a 1-min sliding median filter. The filtered data were used to identify gait bouts and as the synchronization signal with EMG. Gait bouts were subsequently identified from the acceleration synchronization signal by creating a rectangular (0, 1) signal with all values set to 0 initially, and by setting any data point with a value between 0.06 and 0.5 g to 1 (Belavý et al., 2017). This rectangular signal was convolved with 5-min long array of ones (=60 ones), and all continuous epochs where the convolved value was at least one and less than the array length (=59) were considered as potential gait bouts (habitual walking MAD). The approach was developed by experimentation and confirmed to identify gait bouts as described below.

EMG and Acceleration Data Synchronization

The EMG and the accelerometer data were synchronized based on the recorded signals. First, a 1-min sliding median filter was run on each EMG channel, subsequently, data points were linearly interpolated once every 5 s, and finally, the mean of the interpolated data points was used as the EMG synchronization signal. Sliding concordance correlation coefficient was calculated (using a custom-written java implementation https://github.com/tjrantal/concordancecorrelationcoefficient) between the middle 90% of whichever synchronization signal was shorter on the longer synchronization signal, and the lag to the maximum concordance correlation coefficient was used to synchronize the EMG and acceleration signals (Figure 1). The raw resultant acceleration and minimum filtered 100-ms root mean squared EMG values of all four EMG channels were visualized to confirm that the activity was indeed walking, and epochs with simultaneous stable EMG and accelerometry signals were manually segmented (i.e., a particular bout did not necessarily result in at least 5 min of segmented signal) and used in further analyses as the free-living gait bouts (habitual walking EMG and MAD). Based on the visual inspection, days in which synchronization was faulty were discarded.

Sample Size

We estimate that a minimum of eight participants per group is required for a 90% power to detect a difference of 80 mg in MAD between low-average fit and excellent fit groups, assuming a SD of 50 mg.

Statistical Analyses

Statistical analyses were performed in RStudio (version 1.3.1093; RStudio, PBC, Boston, MA). Statistical significance was set at $p < .05$ (two-tailed). Homogeneity of variance was confirmed with Levene’s test. Repeated-measures correlation ($r_m$; Bakdash & Marusich, 2017) was calculated for treadmill walking EMG and MAD values. Differences in walking MAD and EMG by aerobic fitness group factor were compared with analysis of variance and unpaired $t$ test (MAD) or Kruskal–Wallis test and unpaired Wilcoxon test (given the heterogeneity of variances in VO$_2$ and EMG), adjusting for multiple comparisons. Linear multivariable regression models examined associations between VO$_2$max and leg press max (nonscaled, scaled to body mass, and scaled to skeletal muscle mass) with habitual walking EMG and MAD adjusted for age and sex. Logarithmic transformations were applied on relative to skeletal muscle mass VO$_2$max (in milliliters per kilogram per skeletal muscle mass per minute) to meet normality criteria. Standardized coefficients are presented.

Results

Descriptive variables by fitness group are presented in Table 1. The average VO$_2$max was 25.3 ml/kg/min for low–average fit, 42.6 ml/kg/min for good fit, and 48.3 ml/kg/min for excellent fit groups. A higher proportion of low–average and high-fit group participants were men, whereas most of the excellent fit group participants were women. The age range in the total sample was 21–76 years. The participants in the low-average fit group were older, had a higher body weight, BMI, fat percentage, and waist circumference, as compared with the excellent fit group (Table 1).

Repeated-measures correlation coefficient ($r_m = .65$; 95% confidence interval [.49, .76], $p < .001$) showed that treadmill walking EMG and MAD were correlated within individuals. That is, both EMG and MAD increased with increasing treadmill walking speed within individuals.

Figure 2 presents the differences in treadmill walking (4–6 km/ hr) VO$_2$ (percentage of VO$_2$max), MAD, and EMG values, as well as habitual walking MAD and EMG values between the fitness groups. Low-average fit participants had a higher relative to maximum VO$_2$ and EMG during all treadmill walking loads as compared with both good and excellent fit participants ($p < .01$). There was no difference in treadmill walking MAD on any loads. However, during habitual walking bouts, the low–average fit participants had a lower MAD value (245 ± 64.3 mg) as compared with both good fit (316 ± 69.5 mg, $p < .05$) and excellent fit participants (313 ± 68.1 mg, $p < .05$). However, low–average fit participants had a higher relative habitual walking EMG (17.6 ± 10.3 %EMG$_{MVC}$) as compared with good fit participants (9.48 ± 4.22 %EMG$_{MVC}$), yet the difference to excellent fit participants (13.0 ± 8.58 %EMG$_{MVC}$) and overall was not significant (Kruskal–Wallis $p = .10$; Figure 2).

Standardized linear regression models are presented in Figure 3 and Supplementary Table S1 (available online). The VO$_2$max was positively associated with habitual walking MAD in all scaling scenarios independent of age and sex ($p < .01$). The VO$_2$max was not associated with habitual walking EMG, and leg press max was not associated with habitual walking MAD, or EMG, in any scaling scenarios independent of age and sex (see Figure 3 and Supplementary Table S1 [available online]).

Discussion

Accelerometers have enabled monitoring of habitual walking intensity, but these measures are in absolute terms rather than concerning relative physiological effort. The present study aimed to measure walking bouts during normal daily living conditions and compare the walking bout intensity between low-average and excellent fit groups. In line with the hypothesis, those with an excellent aerobic fitness level were walking on average with 28% (245 vs. 313 mg) higher accelerometer-derived absolute intensity, as compared with those with a low-average aerobic fitness level. Physical activity is defined as elevated energy expenditure caused by muscle activity (Caspersen et al., 1985). Along with the
Key activity increases linearly with increasing physical activity intensity expenditure in changing terrains (Bigland-Ritchie & Woods, 1976; Tikkanen et al., 2014), and the relative nature of EMG enables a more truthful comparison of muscle activity between individuals of different aerobic fitness levels. However, when comparing relative physical activity measured with other physiological measures (like heart rate corresponding to 40% to <60% of oxygen uptake reserve), such differences in physical activity level are much smaller or nonexistent (Kujala et al., 2017). The present findings show that individuals with different aerobic fitness levels have a similar relative to maximum muscle activity during habitual walking, which is an important contributor to total physical activity level, and is associated with considerable health benefits, despite absolute accelerometer-derived walking intensity is lower in those with low-average aerobic capacity.

VO₂max is positively associated with body size. A common procedure is to scale VO₂max to bodyweight to express aerobic capacity independent of body weight. However, in people with high body fat content, such an approach can result in underestimated aerobic capacity, given that oxygen uptake during physical activity is driven by metabolically active tissue, not by total body weight (Vanderburgh & Katch, 1996). Scaling VO₂max to skeletal muscle mass may be a more precise method to compare aerobic fitness between people of different body sizes and compositions. We found a consistent, positive association between accelerometer-measured absolute habitual walking intensity and VO₂max. These estimations of absolute physical activity can lead to underestimated physical activity in those with a lower aerobic fitness level. However, when comparing relative physical activity measured with other physiological measures (like heart rate corresponding to 40% to <60% of oxygen uptake reserve), such differences in physical activity level are much smaller or nonexistent (Kujala et al., 2017). The present findings show that individuals with different aerobic fitness levels have a similar relative to maximum muscle activity during habitual walking, which is an important contributor to total physical activity level, and is associated with considerable health benefits, despite absolute accelerometer-derived walking intensity is lower in those with low-average aerobic capacity.

Table 1. Summary Descriptive Table by Aerobic Fitness Group

<table>
<thead>
<tr>
<th>Gender</th>
<th>Low-average</th>
<th>Good</th>
<th>Excellent</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n = 11</td>
<td>n = 14</td>
<td>n = 15</td>
<td></td>
</tr>
<tr>
<td>Women</td>
<td>4 (36.4%)</td>
<td>4 (28.6%)</td>
<td>11 (73.3%)</td>
<td>.037</td>
</tr>
<tr>
<td>Men</td>
<td>7 (63.6%)</td>
<td>10 (71.4%)</td>
<td>4 (26.7%)</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>61.1 (17.0)</td>
<td>44.1 (16.1)</td>
<td>45.5 (14.6)</td>
<td>.022</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>172 (9.56)</td>
<td>176 (7.99)</td>
<td>168 (5.97)</td>
<td>.062</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>76.8 (10.9)</td>
<td>73.3 (11.7)</td>
<td>65.2 (9.51)</td>
<td>.024</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>25.8 (2.65)</td>
<td>23.7 (2.20)</td>
<td>22.9 (2.30)</td>
<td>.011</td>
</tr>
<tr>
<td>Fat mass (kg)</td>
<td>20.5 (9.19)</td>
<td>16.5 (7.64)</td>
<td>12.0 (5.86)</td>
<td>.023</td>
</tr>
<tr>
<td>Fat percentage (%)</td>
<td>26.8 (11.0)</td>
<td>20.5 (4.18)</td>
<td>18.0 (7.64)</td>
<td>.025</td>
</tr>
<tr>
<td>Skeletal muscle mass (kg)</td>
<td>31.3 (7.43)</td>
<td>32.9 (6.77)</td>
<td>29.9 (4.58)</td>
<td>.442</td>
</tr>
<tr>
<td>Waist circumference (cm)</td>
<td>91.8 (8.93)</td>
<td>84.9 (8.07)</td>
<td>78.0 (8.27)</td>
<td>.001</td>
</tr>
<tr>
<td>Grip strength (kg)</td>
<td>49.0 (15.2)</td>
<td>47.6 (13.4)</td>
<td>41.1 (8.54)</td>
<td>.220</td>
</tr>
<tr>
<td>VO₂max (ml/kg/bw-min)</td>
<td>25.3 [20.8, 28.8]</td>
<td>42.6 [37.1, 50.1]</td>
<td>48.3 [39.1, 53.6]</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>VO₂max (ml/kg/smm-min)</td>
<td>60.2 [53.4, 73.3]</td>
<td>94.8 [83.1, 109]</td>
<td>106 [89.7, 113]</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>VO₂max (ml/min)</td>
<td>2117 (937)</td>
<td>3208 (980)</td>
<td>3057 (691)</td>
<td>.008</td>
</tr>
<tr>
<td>Leg press max (kg)</td>
<td>443 (190)</td>
<td>445 (143)</td>
<td>410 (107)</td>
<td>.771</td>
</tr>
<tr>
<td>Leg press max (kg/kg-bw)</td>
<td>5.68 (1.98)</td>
<td>6.02 (1.39)</td>
<td>6.34 (1.67)</td>
<td>.610</td>
</tr>
<tr>
<td>Leg press max (kg/kg-sm)</td>
<td>13.7 (3.55)</td>
<td>13.5 (3.27)</td>
<td>13.9 (3.95)</td>
<td>.969</td>
</tr>
<tr>
<td>EMG MVC (μV)</td>
<td>208 (98.9)</td>
<td>276 (85.1)</td>
<td>289 (92.0)</td>
<td>.080</td>
</tr>
<tr>
<td>Recorded days</td>
<td>1.73 (0.79)</td>
<td>1.50 (1.09)</td>
<td>1.87 (1.41)</td>
<td>.694</td>
</tr>
<tr>
<td>Recording time per day (hr)</td>
<td>10.2 (2.01)</td>
<td>12.5 (1.83)</td>
<td>11.9 (2.23)</td>
<td>.032</td>
</tr>
<tr>
<td>Gait bouts (nro)</td>
<td>4.32 (3.44)</td>
<td>4.55 (5.70)</td>
<td>3.41 (2.77)</td>
<td>.745</td>
</tr>
<tr>
<td>Gait bout duration (min)</td>
<td>0.95 (1.00)</td>
<td>0.87 (1.25)</td>
<td>0.99 (0.91)</td>
<td>.953</td>
</tr>
</tbody>
</table>

Note. bw = body weight; smm = skeletal muscle mass; BMI = body mass index; VO₂max = peak oxygen uptake; EMG MVC = maximal voluntary contraction electromyography. Boldface indicates statistical significance at p < .05.

*aSignificant difference as compared with low-average aerobic fitness group. †Significant difference as compared with good aerobic fitness group.

In previous studies, accelerometry-measured absolute total physical activity level has been higher in men than women, decreased by BMI, and increased by aerobic fitness level (Dyrstad et al., 2016; Kujala et al., 2017; Tucker et al., 2011; Vaara et al., 2020). Such estimations of absolute physical activity can lead to underestimated physical activity in those with a lower aerobic fitness level. However, when comparing relative physical activity measured with other physiological measures (like heart rate corresponding to 40% to <60% of oxygen uptake reserve), such differences in physical activity level are much smaller or nonexistent (Kujala et al., 2017). The present findings show that individuals with different aerobic fitness levels have a similar relative to maximum muscle activity during habitual walking, which is an important contributor to total physical activity level, and is associated with considerable health benefits, despite absolute accelerometer-derived walking intensity is lower in those with low-average aerobic capacity.
The reason why higher fit individuals walk at a higher absolute intensity may be related to individual energy cost optimization strategies. People typically choose to walk at speed and frequency that improves elastic energy utilization in plantar flexor muscles (Neptune et al., 2008; Russell & Apatoczky, 2016) and optimizes energy consumption per unit distance covered (Lieberman & Bramble, 2004). On average, this optimization occurs at intensities below the lactate threshold (Åstrand et al., 1977), which is on average higher in high-fit individuals. Moreover, the pleasure to exercise is reduced when intensity exceeds the lactate threshold (Ekkekakis et al., 2011).

Maximal lower-extremity strength was not associated with absolute accelerometer derived or relative to maximum EMG-derived habitual walking intensity. The muscle activity was on average 13% of EMG_{MVC} during habitual walking. While this level of activation is high enough for health adaptations (Bailey & Locke, 2015; Pulsford et al., 2017), it may be low enough to be unaffected by lower-extremity strength in this age group. However, a positive association between maximal lower-extremity strength and preferred walking speed has been reported in a group of 20–79 year old men and women (Bohannon, 1997). It is important to note that preferred walking speed measured in lab conditions may not represent habitual walking during daily life. Moreover, multiple regression analyses adjusting for age were not reported previously (Bohannon, 1997). Of the regressions reported, weight, height, sex, and nondominant hip abduction strength provided the best overall explanation for preferred walking speed (Bohannon, 1997). Therefore, the isometric leg press used as a

Figure 2 — Differences in VO2, MAD, and EMG between fitness groups in treadmill walking and habitual walking bouts. EMG = electromyography; MAD = mean amplitude deviation.

![Figure 2](image-url)
The novel aspect of the present study was measuring physiological effort of walking directly from the large lower-extremity muscle groups, the quadriceps, and the hamstring muscle groups. The average muscle activity level during daily life is low, below 4% of maximal muscle activity capacity when assessed from lower-extremity muscle groups of physically active adults (Pesola et al., 2015; Tikkanen et al., 2013), and can be considerably lower in particular muscles (Kern et al., 2001). Muscle activation was on average 13% of maximum during the habitual walking periods of the present study, suggesting that walking can effectively increase the daily muscle activity level. Figure 2 shows that EMG was already relatively high at 4 km/hr walking on a treadmill (5.7–15.5 %EMG_{MVC}), and the confirmed bouts resulted in an intensity considered as

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Figure 3 — Standardized linear regression analyses examining the associations between absolute (a), relative to body mass (b), and relative to skeletal muscle mass (c) VO2 max and leg press max with habitual walking MAD and EMG intensities. EMG = electromyography; MAD = mean amplitude deviation.
moderate to vigorous activity (at minimum), which corresponded to walking at 6 km/hr on a treadmill. Hence, walking requires significant muscle activity already at slow walking speed, and targeting walking for exercise and commuting has a meaningful public health message potential. Over a 1-km distance, for example, walking instead of driving a car requires 3.3 times more oxygen and yields 3.5 times higher mean muscle activity level (Tikkanen et al., 2016). The habitual at least 5-min walking bouts measured in the present study could provide a meaningful physiological stimulus for muscles. Future studies should test whether a given absolute or relative intensity of walking can improve health across people with different aerobic fitness levels (Oja et al., 2018).

The visually recognized walking periods only represent conscious rather prolonged (minimum 5 min) walking bouts and the actual duration of walking included in the present analyses was short and only a proportion of total daily walking. While such walking bouts do not represent slow ambulation (Tudor-Locke et al., 2011), they are comparable or slightly faster to walking bouts people on average do for exercise or commuting (Tudor-Locke & Rowe, 2012). EMG recordings of the present study represent only quadriceps and hamstring muscle groups and are not representative of other lower- or upper-extremity muscles that are also important for walking behavior. The sample size for EMG was for exploratory purposes, and some of the null findings may be due to small sample size and/ or high variance in the data. The sample is quite heterogeneous in terms of age and sex and although age- and sex-specific fitness categories and adjustment were used, these may not remove all confounding and other categorization conventions should be tested (Kokkinos et al., 2018). While these findings would need to be confirmed in future studies, the present data provide a potential avenue into understanding why some people walk at a higher intensity, and therefore get greater health benefits, during their daily life. In particular, the present results stress the importance of physical activity intensity evaluation based on relative to fitness rather than absolute criteria. Provided the strong association between habitual walking acceleration and maximal aerobic fitness, habitual walking could serve as a practical reference point for accelerometer intensity normalization to better reflect relative to fitness physical activity levels (Haapala et al., 2020).

Conclusions

We found that people with an excellent aerobic fitness level walk with a higher absolute accelerometer-derived intensity during their daily living as compared with those with a low-average fitness level. However, relative to maximum muscle activity of habitual walking is on average 13% of maximal voluntary effort in all adults regardless of aerobic fitness level and tends to be higher in those with a low-average aerobic fitness. These findings have implications for research and practice. Researchers should aim at measuring habitual behavior, like walking intensity, in relation to aerobic fitness capacity. This would enable investigating the health effects of relative to maximum intensity of activity, which can be differently associated with health than when activity is measured in absolute terms. Professionals providing walking prescriptions should be mindful that low-fit persons can have a lower accelerometer-derived walking intensity as compared with their high-fit peers, although their relative walking effort would be the same. For low- and high-fit persons, habitual walking can provide a significant physiological stimulus for muscles.

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References


